

Airborne Wind Shear Detection and Warning Systems

*Third Combined Manufacturers'
and Technologists' Conference*

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(NASA-CF-10060-Pt-1) AIRBORNE WIND SHEAR
DETECTION AND WARNING SYSTEMS: THIRD
COMBINED MANUFACTURERS' AND TECHNOLOGISTS'
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FOREWORD

The Third Combined Manufacturers' and Technologists' Conference was hosted jointly by NASA Langley Research Center (LaRC) and the Federal Aviation Administration (FAA) in Hampton, Virginia on October 16-18, 1990. The meeting was co-chaired by Dr. Roland Bowles of LaRC and Herbert Schlickemaier of the FAA. Dan Vicroy of LaRC served as the Technical Program Chairperson and Carol Lightner of the Bionetics Corporation was the Administrative Chairperson.

The purpose of the meeting was to transfer significant ongoing results of the NASA/FAA joint Airborne Wind Shear Program to the technical industry and to pose problems of current concern to the combined group. It also provided a forum for manufacturers to review forward-look technology concepts and for technologists to gain an understanding of the problems encountered by the manufacturers during the development of airborne equipment and the FAA certification requirements.

The present document has been compiled to record the essence of the technology updates and discussions which followed each. Updates are represented here through the unedited duplication of the vugraphs, which were generously provided by the respective speakers. When time was available questions were taken from the floor; if time was not available questions were requested in writing. The questions and answers are included at the end of each presentation. A general question and answer session was conducted at the end of each day and is included at the end of report along with closing remarks.

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Session I. Terms of Reference

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Airline Industry Intentions
Frank Tullo, Air Transport Association

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AIRLINES APPLYING FOR EXEMPTION FROM WIND SHEAR REQUIREMENTS

AMERICAN AIRLINES

CONTINENTAL AIRLINES

EASTERN AIRLINES

NORTHWEST AIRLINES

AMERICAN AIRLINES

FORWARD LOOKING INFRARED SENSORS

TURBULENCE PREDICTION SYSTEMS (TPS)

3 MD-80'S RECORDING DATA

TRANSPARENT TO FLIGHT CREWS

SIGNIFICANT EVENT MARKER

NORTHWEST AIRLINES

REACTIVE AND FORWARD LOOKING INFRARED

HONEYWELL REACTIVE SYSTEM

INFRARED - TPS

DATA COLLECTOR

PILOT REPORT FOR EVENTS

EASTERN AIRLINES

BENDIX DOPPLER RADAR

B-757

FORWARD SWEEP WX

REVERSE SWEEP DOPPLER

CONTINENTAL AIRLINES HAS SIGNED A MEMORANDUM OF UNDERSTANDING FOR

DOPPLER RADAR WITH

- BENDIX 23 AUG 1990
- COLLINS 22 JUN 1990

INFRARED WITH

- HONEYWELL - KOLLSMAN 20 JUL 1990
- SUNDSTRAND - COLORADO
STATE UNIVERSITY 22 JUN 1990

THESE MOU'S PROVIDE FOR A FLIGHT EVALUATION PROGRAM OF BOTH TECHNOLOGIES. AT THE PRESENT TIME, BOTH APPEAR VIABLE. THEY WILL FLY COUPLED WITH REACTIVE SYSTEMS WHICH ARE PRESENTLY CERTIFIED TO FAR 121.358 COMPLIANCE.

HONEYWELL - KOLLSMAN

AIRCRAFT 788, B727-200, WILL RECEIVE AN
INSTALLATION PACKAGE CONSISTING OF:

- HONEYWELL REACTIVE
WIND SHEAR COMPUTER
- KOLLSMAN FLIR SENSOR
- DATA RECORDER

PRESENT SCHEDULE

- APPLICATION FOR STC, 10 SEP 1990
- INSTALLATION AND CERTIFICATION,
NOV - DEC, 1990
- REVENUE FLIGHTS AND DATA COLLECTION,
JAN - DEC 1991
- FINAL REPORT, OCT 1991

SUNDSTRAND - CSU

ONE OF OUR B737-300 AIRCRAFT, WHICH HAS THE SUNDSTRAND MKV WIND SHEAR SYSTEM (BOEING ALGORITHM) INSTALLED WILL BE UTILIZED. THE INSTALLATION PACKAGE WILL CONSIST OF:

- CSU INFRARED SENSOR
- SUNDSTRAND MKV (SUNDSTRAND ALGORITHM) WIND SHEAR COMPUTER
- OPTICAL DISK RECORDER

PRESENT SCHEDULE:

- COMPLETE CSU SENSOR FLIGHT TRIALS, NOV 1990
- PRELIMINARY 737-300 SYSTEM INSTALLATION DESIGN, DEC 1990
- APPLICATION FOR STC, JAN 1991
- COMPLETE FABRICATION, ASSEMBLY, AND TEST OF SYSTEM COMPONENTS FOR 737-300 INSTALLATION, APR 1991
- 737-300 INSTALLATION BUY-OFF, MAY 1991
- INITIATE 737-300 REVENUE FLIGHTS AND DATA COLLECTION, JUN 1991
- COMPLETE DATA COLLECTION AND REMOVAL OF 737-300 INSTALLATION, OCT 1991
- FINAL EVALUATION REPORT, NOV 1991

COLLINS

ONE OF B737-300 AIRCRAFT, WHICH HAS THE SUNDSTRAND MKV WIND SHEAR SYSTEM (BOEING ALGORITHM) WILL BE UTILIZED. DETAILS OF THE INSTALLATION HAVE NOT BEEN WORKED OUT AS OF THIS TIME. A PLAN TO UTILIZE THE AIRCRAFT WHICH HAS THE SUNDSTRAND CSU SYSTEM INSTALLED FOR THIS EVALUATION ALSO IS BEING PURSUED. PRESENT PLANS WILL ALLOW FOR SYSTEM INSTALLATION IN APRIL 1991.

BENDIX

ONE OF THE B737-300 AIRCRAFT, WHICH HAS THE SUNDSTRAND MKV WIND SHEAR SYSTEM (BOEING ALGORITHM) WILL BE UTILIZED. THE INSTALLATION PACKAGE WILL CONSIST OF:

- BENDIX 708 RADAR
- RECORDER - CONTROL SYSTEM

PRESENT SCHEDULE:

- R/T MODIFICATION, MAR 1991
- FLIGHT TESTS (BENDIX), JUN 1991
- INSTALLATION AT CONTINENTAL, JUL 1991
- REVENUE FLIGHTS AND DATA COLLECTION, JUL - NOV, 1991
- FINAL REPORT, DEC 1991

PROBLEM AREAS

INFRARED SENSOR - DE-ICE REQUIREMENTS

DOPPLER RADAR - ARINC 708

- TSO CERTIFICATION
- WEATHER TSO UNCHANGED
- MODIFY DOPPLER FUNCTION ONLY
- CONTROL FROM INSTALLATION PACKAGE
- BLIND TO FLIGHT DECK
- FORWARD SWEEP - WX
- REVERSE SWEEP - DOPPLER W/S

FAA EXEMPTION

DATA - WHO AND WHOM

Airline Industry Intentions - Questions and Answers

Q: ED LOCKE (Thermo Electron Technologies) - Are there any studies that indicate the degree to which abortive landings impact the finances of the airlines? Pilots that choose to not make a landing because the conditions are suggestive of wind shear problems and therefore connections are lost and so on, and so on. Are there any studies that you are aware of that do put some numbers to that?

A: FRANK TULLO (ATA) - There are none that I'm aware of. There are large economic consequences of landing at an alternate airfield and subsequent problems of taking care of the passengers. I don't know of any study.

Q: WALT OVEREND (Delta Airlines) - What are the advantages to those airlines who have now or whom have applied for exemptions to install predictive systems if the FAA will not or has stated they will not certify such systems?

A: FRANK TULLO (ATA) - That's an excellent question. I haven't got an answer for that but you're right, there is no incentive. I'm hoping that this is a typical FAA posturing where they're holding our feet to the fire and making us prove to the world that a system, whatever system that is, can stand alone in predicting wind shear. Obviously there is no economic advantage to this exemption if the end result is that we have to carry both reactive and predictive. Hopefully we won't have to.

Q: WALT OVEREND (Delta Airlines) - Is there not more positive methods and resultant better indications of wind shear conditions from ground systems than from those that can be carried by each aircraft? How long does it take to develop TWDR - Is the program on schedule?

A: FRANK TULLO (ATA) - I would like to ask that same question. I know that in the middle '80s the industry decided to embark on a multifaceted attack on wind shear. One was pilot education and then ground based equipment and then airborne based equipment. I believe we've done as much as we can possibly do with pilot education. The fact that we haven't had an accident in 62 or 63 months is indicative of that. I know that there is terminal Doppler radar available and I know that it has been proven successful. I don't know where that program stands. Can anybody enlighten us on that?

A: STEVE CAMPBELL (MIT Lincoln Laboratory) - The TDWR program has been going on since about 1985 or a little bit earlier and it's really been proceeding at a record breaking rate for an FAA program. It is anticipated that the first TDWRs will be installed at the end of 1992 and one of the reasons this is likely to happen is that Ratheon has a substantial incentive to in fact deliver at that time. If they deliver the first several units in that time frame they get a substantial financial incentive, so they have quite a bit of incentive to actually have that happen. It is an accelerated development program and it seems to be pretty much on track from what we can tell. I should say one other thing about the impact of microbursts on airport operations, we haven't assessed this in any tremendous detail except to say that even in a place like Orlando where you have a tremendous number of events, the number of hours in the year where microbursts actually impact the airport is rather small, it's only a matter of 10 or 20 hours. I don't have the actual hours at my fingertips, but in the grand scheme of things it is a very small period of time and so there may be a transitional impact upon airport operations but it's not one of these things, for instance when weather comes in and impacts an airport, that lasts for a long time, fog for example, one foggy day can cause a lot more impact than a whole summer of microbursts.

ROLAND BOWLES (NASA Langley) - Walt; the second part of the question you asked, as I understand it was. What's the trade off between ground detection and information dissemination and airborne? Why have both? I might point out that after 1975 the FAA put together a major wind shear program initiative. I think we declared victory in about 1979. Then came Pan Am at New Orleans and Dallas and other recent near misses or recent encounters. So the point is that we've got something going here now on the technology side, let's go ahead and get the problem solved and get it behind us. There are other things out there to work on. I might point out that the policy has been made. We are going to have 47 Doppler radars deployed at major TCAs and there is an equipment rule that says if you're going to operate under 121 rules you're going to have airborne equipment. This issue is not whether or not you're going to have the equipment, it's what equipment are you going to have that gives maximum safety per unit dollar.

Q: UNKNOWN - What are the advantages of airborne equipment?

A: FRANK TULLO (ATA) - As a pilot I like to be as autonomous as possible. The weakest link is the transfer of information and all too often that information is not received by the pilot or if it is received it's not understood by the pilot. One glance down at a device that shows me the threat and where it is in relation to me is so much more important than somebody giving me a subjective view of what they see on an instrument in their suite.

Q: (unable to understand)

A: FRANK TULLO (ATA) - I believe that's why four of the airlines have elected to take a chance on other technology because we are not quite satisfied with what we have right now. It is better than nothing, I'll say that. I heard it mentioned a number of times, we've gotten an awful lot out of our pilot training effort. I think that's reaped a lot of benefits.

SAM SAINT (Safe Flight Instrument Corp.) - I made a careful study of the eight major accidents from Eastern 66 in '75 to Delta 191 in '85 and the question I was asking when I went through that was "would it be likely that this accident would have happened if the airplanes had been equipped with a reactive warning system?" I couldn't find one accident in that long list that looked like it had even a chance of happening. I delivered a paper that said this at a meeting in Paris and I still believe it.

Session I. Terms of Reference

Wind Shear Program in France

Overview

Bernard Ades, DGAC/SFACT

LIDAR Studies on Microbursts

Y. Aurenche and J.L. Boulay, ONERA

RADAR Performance Experiments

C. Le Roux, DGAC/STNA

MEGASODAR Experiment

Alain Donzier, REMTECH

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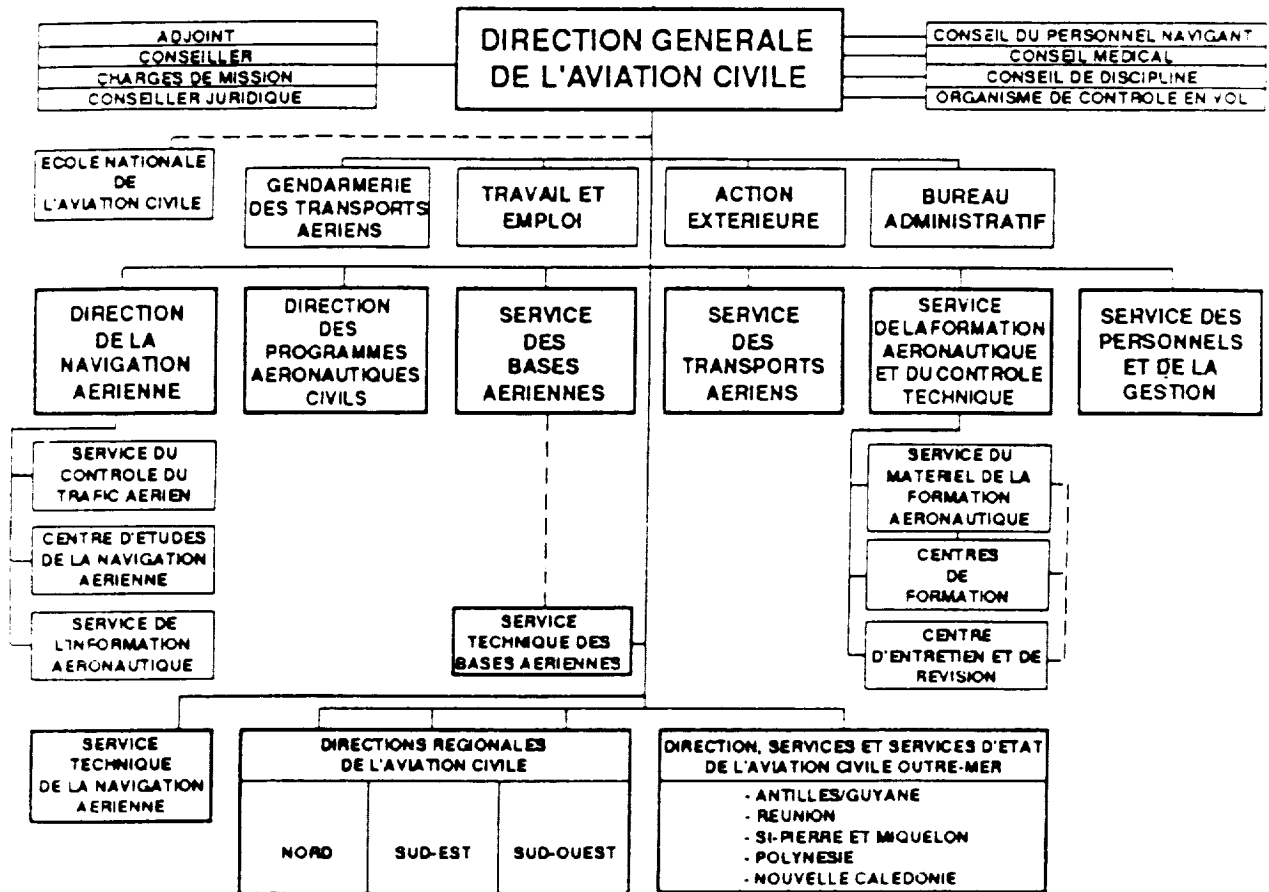
Wind Shear Program in France

Overview

Bernard Ades, DGAC/SFACT

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MINISTRE DE L'EQUIPEMENT, DU LOGEMENT,
DES TRANSPORTS ET DE LA MER



WINDSHEAR PHENOMENOM IN FRANCE

■ METEOROLOGICAL DATA ANALYSIS

■ ACTING METEOROLOGICAL OFFICE

■ 150 KF

■ WORK IN PROGRESS

CERTIFICATION/OPERATIONAL CONFORMITY

- WINDMODEL SELECTION
- FALSE ALARM CRITERIA
- OPERATIONAL IMPACT
- ACTING AEROSPATIALE/CEV
- 1150 KF
- WORK PARTLY ACHIEVED

WINDSHEAR OPERATIONAL PROCEDURES

■ MODERN AIRCRAFT

■ ACTING AEROSPATIALE/AIRBUS

■ 4000 KF

■ WORK JUST BEGUN

LIDAR STUDIES ON MICROBURSTS

- AIRBORNE MODELIZATION/DETECTION

- PLANE BEHAVIOUR

- ACTING ONERA-DGA/DRET

- 2500 KF

- WORK IN PROGRESS

- PRESENTATION BY:

- * Y. AURENCHE (ONERA)

LIDAR STUDIES ON MICROBURSTS

- ELECTRICAL ACTIVITY MEASURES

- DOPPLER RADAR MEASURES

- ACTING:

 - * ONERA-DGA/DRET

 - * LINCOLN LABORATORY

- 1700 KF ON FRENCH SIDE

- WORK IN PROGRESS

- PRESENTATION BY:

 - * JL. BOULAY, P LAROCHE (ONERA)

 - * M. WEBER (LINCOLN LABORATORY)

RADAR PERFORMANCE EXPERIMENTS

- 5 AND 30 CMS RADARS

- ACTING CNET/CRPE

- 2200 KF

- WORK IN PROGRESS

- PRESENTATION BY:

 - * C. LEROUX (STNA)

 - * F. BERTIN (CNET/CRPE)

MEGASODAR EXPERIMENT

■ MULTICELLULAR ANTENNA

■ ACTING REMTECH

■ 875 KF

■ WORK IN PROGRESS

■ PRESENTATION BY:

* A. DONZIER (REMTECH)

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Wind Shear Program in France

LIDAR Studies on Microbursts
Y. Aurenche and J.L. Boulay, ONERA

ONERA's Program about Windshear Studies

Preliminary Analysis of Requirements for Future Airborne Windshear Detection Systems

Y. Aurenche, Binh Dang Vu, D. Guffond
Office National d'Etudes et de Recherches Aérospatiales (ONERA)
Châtillon, FRANCE

1. INTRODUCTION

With DGAC and DRET support, ONERA works since 89 on Windshear problems. The main studies are:

- Flight Mechanics
- Microbursts modeling
- Microburst detection with airborne systems (LIDAR, radar, passive infrared sensors)
- Microbursts prediction with ground systems (VHF interferometry)

The purpose of this presentation is to give a short overview of these studies and some results.

2. FLIGHT MECHANICS

The studies concern the behavior of two airplanes (B727 and A310) equipped with an ILS and crossing a microburst.

A simulation program has been developed, using for each airplane a classical and simplified guidance and flying loop; the loop takes into account the flight maneuvering capabilities in order to realize an automatic approach and to land with a conventional speed.

The principal criteria for a good landing are:

- an angular error with respect to the glide path inferior to 1°
- a vertical impact speed inferior to 7 ft/s

Six windfield models have been considered:

- 3 historical cases; the New York, Dallas, and Atlanta accidents.
- 2 standard FAA cases (AD 120-41); n°6, being the most severe.
- 1 symmetrical RAE model, with the conditions $K_r=1$, $K_x=3$, $K_z=1$, giving a high Severity Factor equal to 0.8 during about 25 seconds.

For each simulation, the parameters are presented versus time and can be analyzed (Fig. 1): horizontal and vertical wind speed, thrust, conventional speed, incidence, trim, etc ...

For the New York case, the Fig. 2 shows:

- the fatal flight path
- the glide path
- the simulated flight path

The simulation conclusion is that, with an ILS and a conventional landing speed, the two airplanes have sufficient performances for following the glide path and landing with acceptable conditions. In certain cases, the impact vertical speed is slightly over the criterion (8 ft/s for Dallas case). But, for all historical and FAA models, the simulation shows that the landing is possible. On the other hand, for the RAE model, the ILS is insufficient.

The next study consisted in equipping the airplane with a forward looking system giving a microburst detection at a certain range R (Fig. 3) and setting off a new flying strategy: that is to command at this time a speed increment dV in function of the Severity Factor measured.

A parametric study has been developed versus R , dV and D , the distance between the microburst core and the runway. The global result for RAE model is presented on the Fig. 4. The speed increment is 20 knots. The two airplanes equipped with an ILS and using this strategy can land with acceptable conditions only if the prediction range is 1.5 Km.

At the present time, the pursuit of this study consists in simulating more severe cases.

3. MICROBURSTS MODELING

In order to study radar and LIDAR beam propagation across microbursts, a modeling program has been developed.

It simulates a vertical dry airflow directed to the ground with three dimensional Navier Stokes equations, in incompressible and instationary form. The domain sizes are 10 by 10 by 5 Km (Fig. 5). The spatial resolution is 200 m but must be reduced. The vertical airflow is initialized by a certain law. The Fig. 6 presents a vertical section and give the speeds and the vortex locations. The Fig. 7 presents the iso-speed profiles.

At present, the task concerns hydrometers introduction in the model by using a regular raindrops injection in airflow. The problem is to know if the instationary wind action on the droplets trajectory does not bring them together and does not give over or under concentration zones.

The calculation hypothesis are:

- the rain drops don't modify the flowfield velocity
- the forces taken into account are gravity and the drag forces produced by drops and air velocity differences.

The Fig. 8 shows the concentration factor C_f at $t=1000s$ and for a 30 m/s injected airflow speed. The over-concentration locations do not correspond with maximal speed location presented on the Fig. 7.

At present, these studies are going on with a smaller spatial resolution.

4. AIRBORNE DETECTION SYSTEMS

Up to now, the activities on this subject have been mainly feasibility studies; no hardware has been developed yet.

5. GROUND PREDICTION SYSTEMS

An experiment campaign using a VHF interferometer has been realized in August 90 at Orlando in cooperation with the Lincoln Laboratory using several radars; the first results are presented in the next paper.

Fig.1

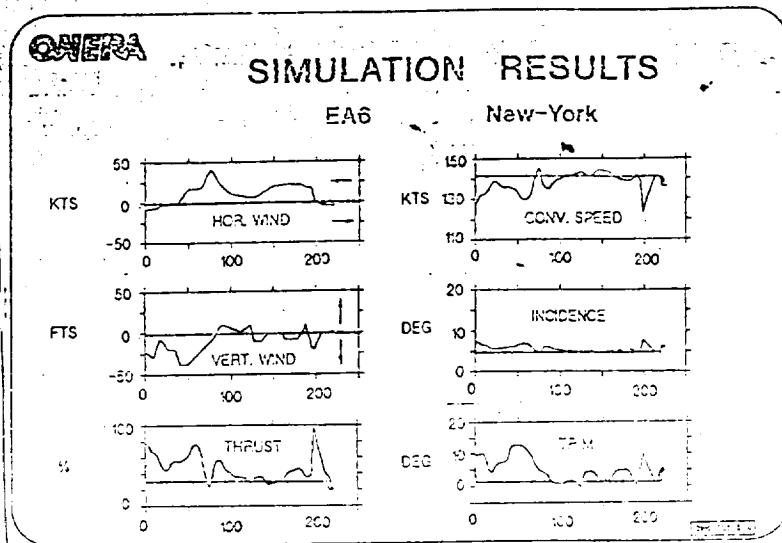


Fig.2

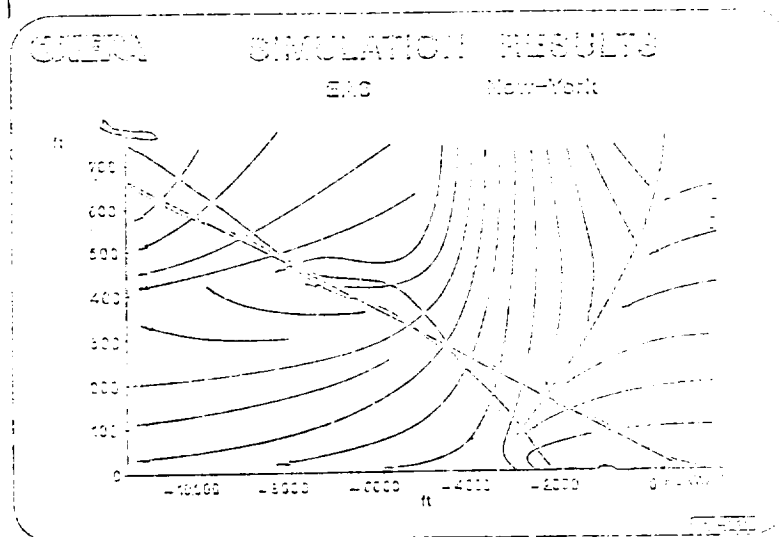


Fig.3

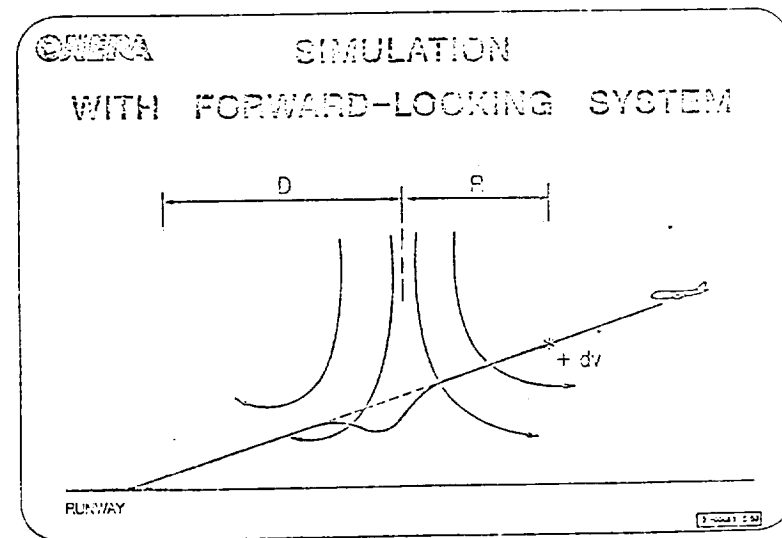


Fig.4

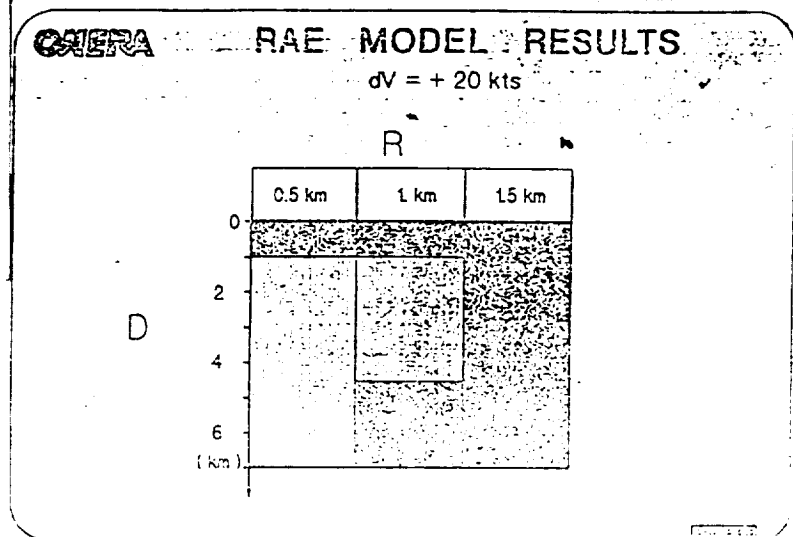


Fig.5

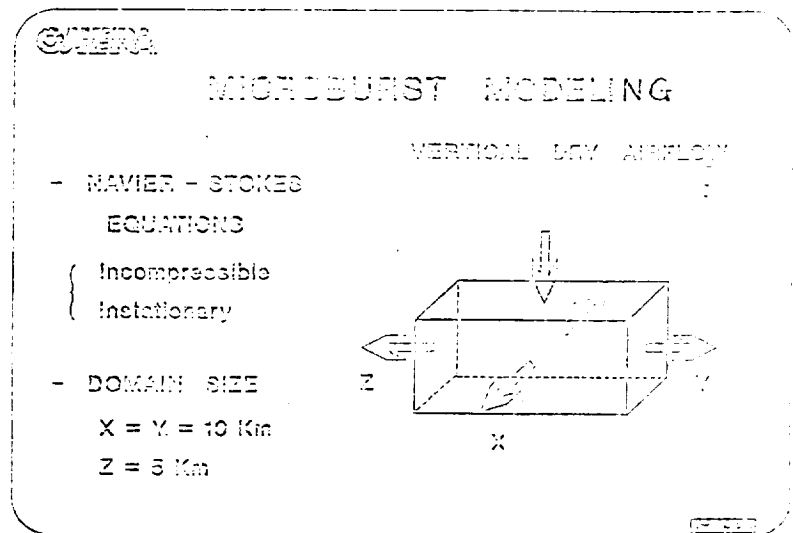


Fig.6

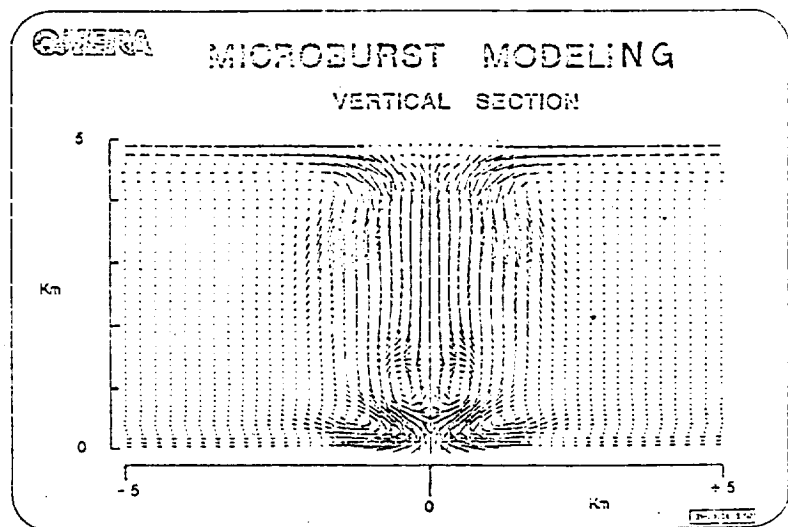


Fig.7

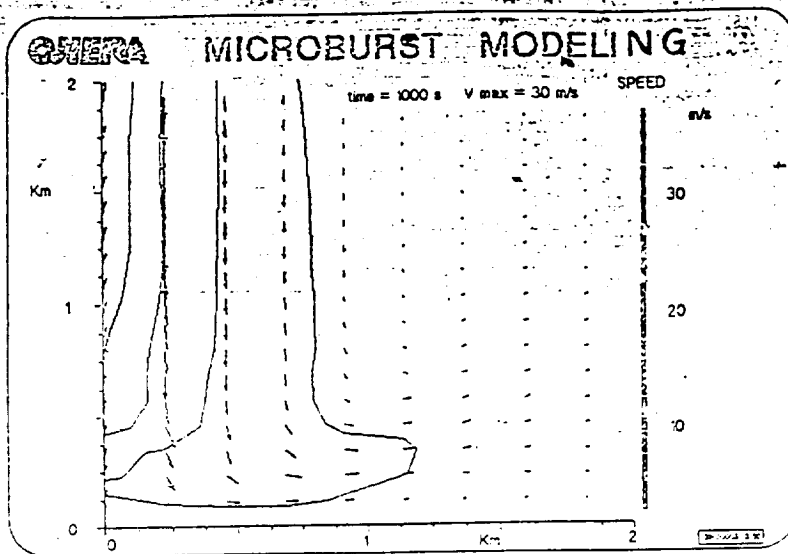
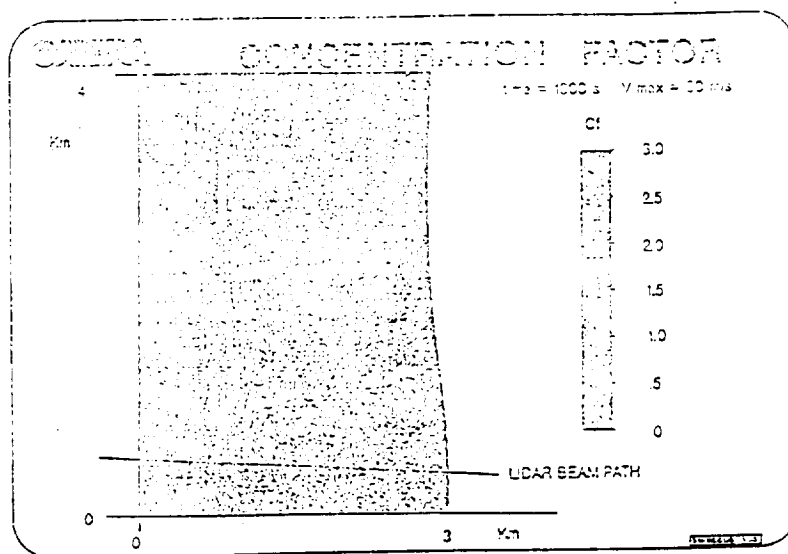


Fig.8



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Wind Shear Program in France

RADAR Performance Experiments
C. Le Roux, DGAC/STNA

**EVALUATION OF 30 cm PROUST DOPPLER RADAR
AND 5 cm RONSARD DOPPLER RADAR AT LOW HORIZONTAL
TILT IN CLEAR AIR AND RAIN LOW LEVEL
WIND SHEAR CONDITION**

C. LE ROUX (1), F. BERTIN (2) and H. MOUNIR (2)

(1) : DGAC/STNA, PARIS

(2) : CNET/CRPE, St MAUR

**EVALUATION OF PROUST DOPPLER RADAR ($\lambda = 30$ CM) AND RONSARD
DOPPLER RADAR ($\lambda = 5$ CM) AT LOW HORIZONTAL TILT IN CLEAR AIR AND
RAIN LOW LEVEL WIND SHEAR CONDITION.**

C. LE ROUX (1) , F. BERTIN (2) and H. MOUNIR (2)

(1) : DGAC/STNA , PARIS

(2) : CNET/CRPE, SAINT MAUR.

Abstract : Theoretical studies and experimental results obtained at Coulommiers airport have shown the capability of Proust radar to detect windshears, in clear air condition as well as in presence of clouds or rain. Several examples are presented:

- In a blocking highs situation we can clearly distinguish an atmospheric wave system at the Brunt-Vaisala frequency.
- In a situation of clouds without rain, we can see easily the limit between clear air and clouds.
- A last example shows a windshear associated with a gust front in rainy condition.

A comparison of 30 cm clear air radar Proust and 5 cm weather doppler radar Ronsard will allow to select the best candidate for windshear detection, taking into account the low sensibility to ground clutter of Ronsard radar.

Résumé : Les études théoriques et les résultats expérimentaux obtenus sur l'aéroport de Coulommiers ont mis en évidence la capacité du radar Proust à détecter les cisaillements de vent, aussi bien par ciel clair qu'en présence de nuages ou de pluie. Plusieurs exemples sont présentés :

- Dans une situation de blocage atmosphérique on distingue clairement un système d'ondes à la fréquence de Brunt-Vaisala.
- Dans une situation nuageuse sans pluie, on discerne aisément la limite entre l'air clair et la masse nuageuse.
- Un dernier exemple montre un cisaillement de vent lié à un front de rafale en situation de pluie.

Une comparaison du radar air clair 30 cm Proust et du radar doppler météorologique Ronsard permettra de sélectionner le meilleur candidat quant à la détection des cisaillements de vent, compte tenu de la moindre sensibilité du radar Ronsard aux échos de sol.

SUMMARY

I) CONTRACT BETWEEN DGAC AND CNET

II) PROUST AND RONSARD RADAR CHARACTERISTICS

**III) RELATIONSHIP BETWEEN CLEAR AIR AND RAIN
REFLECTIVITY**

IV) EXPERIMENTAL RESULTS WITH PROUST RADAR

V) CONCLUSION

CONTRACT BETWEEN CNET AND DGAC

I-PHASE 1

Evaluating performances of "clear air" radars ($\lambda = 30$ cm) for detection of wind shear to prevent hazardous situations to aircraft.

II-PHASE 2

Comparison between PROUST ($\lambda = 30$ cm) and RONSARD ($\lambda = 5$ cm) radars for different meteorological conditions (clear air, convection cells, clouds, rain,...etc).

Application to wind shear detection.

Experimentation : 12/90 ---> 12/91

PROUST AND RONSARD RADAR CHARACTERISTICS

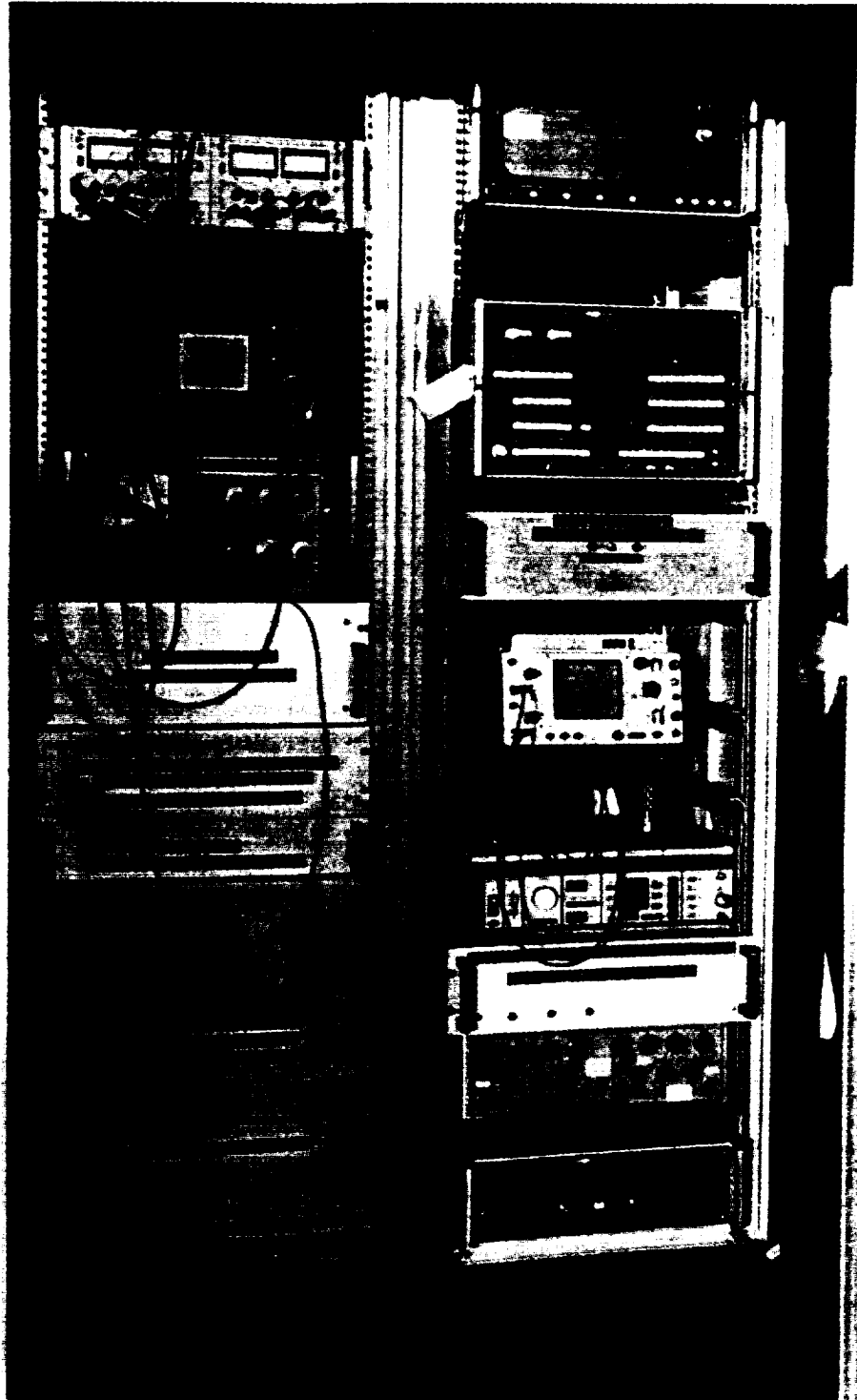
	PROUST	RONCARD
WAVELENGTH (cm)	30	5,4
BEAMWIDTH(°)	5	0,9
PEAK POWER (KW)	4,5	250
PRF (khz)	6,4	0,75 ; 1,5 ; 3
MAX RANGE (km)	20	200 ; 100 ; 50
RANGE RESOLUTION(m)	600	200 ; 100 ; 50
FFT (points)	256	64
VELOCITY RANGE(m/s)	+/-16	+/-10 ; +/-20 ; +/-40
INCOHERENT INTEGRATION	4 to 32	1 to 128
TIME RESOLUTION (s)	5 to 40	0,17 to 22(with PRF ₁ 3 KHz)
MINIMUM DETECTABILITY (DBZ)	-20	0

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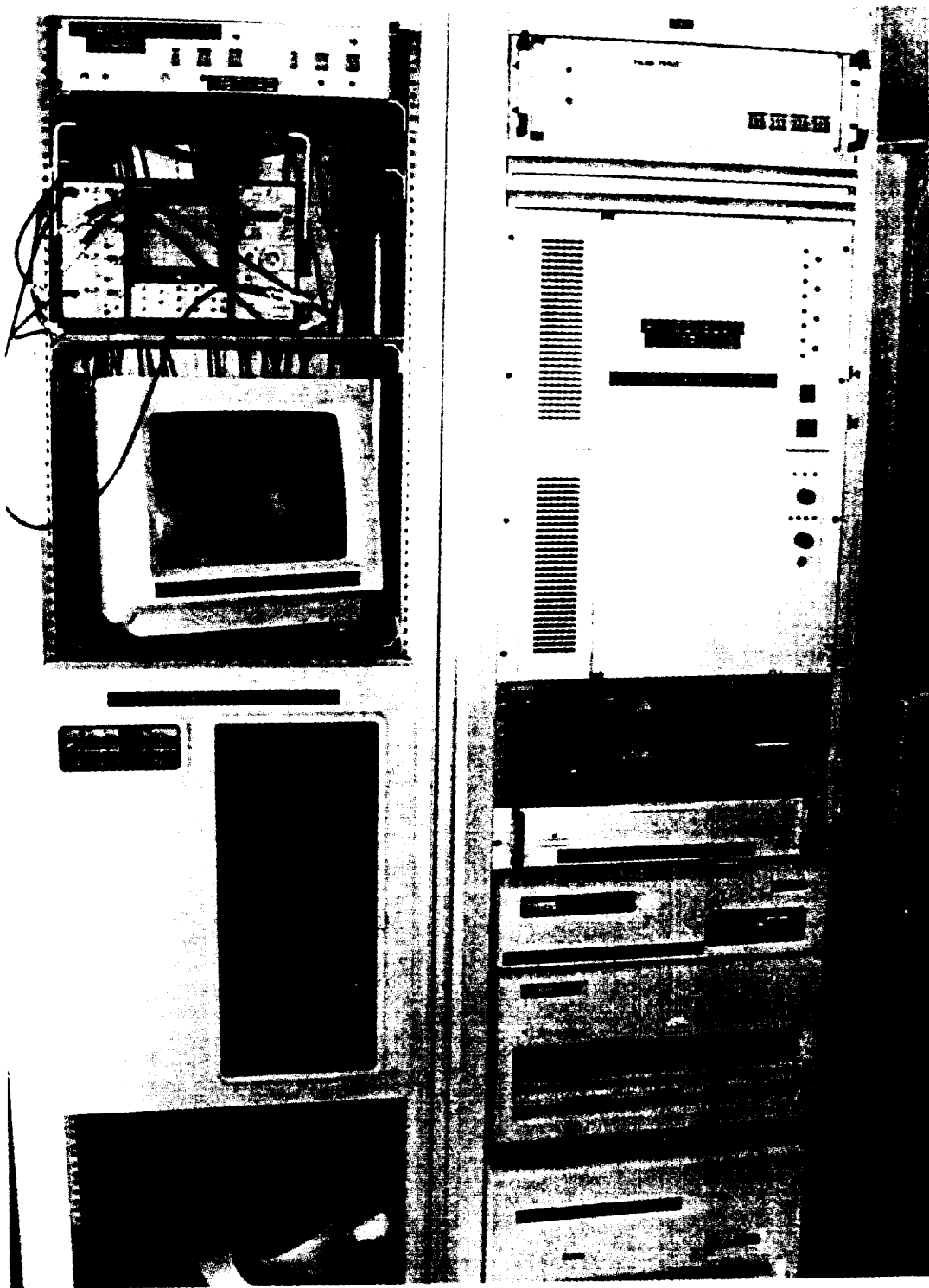
PROUST RADAR AT COULOMMIERS AIRPORT

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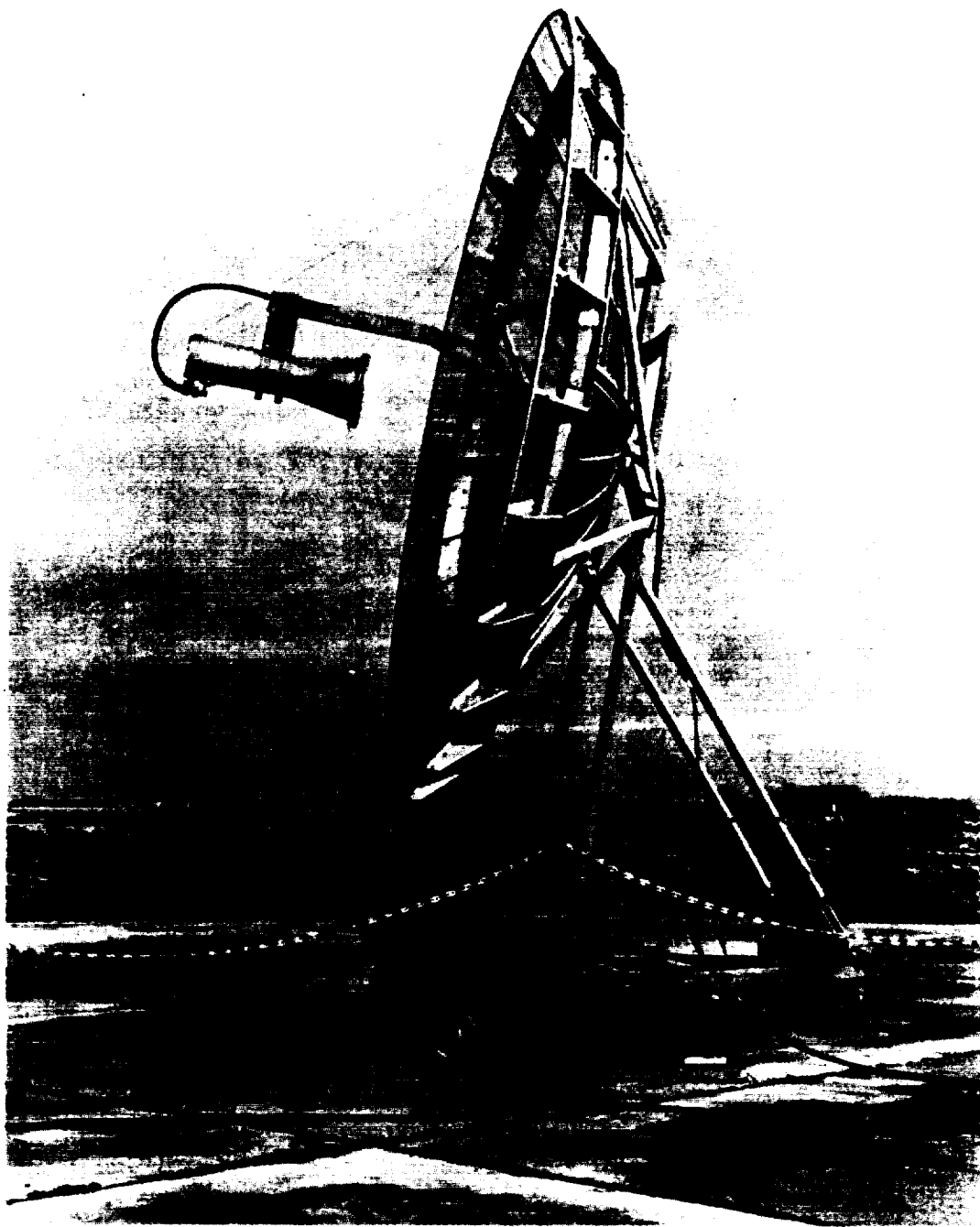


TRANSMITTER AND RECEIVER UNITS OF PROUST RADAR

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NUMERICAL PROCESSING AND CONTROL UNITS OF PROUST
RADAR



4.6 m DIAMETER ANTENNA OF PROUST RADAR
IN COULOMMIERS AIRPORT

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RONARD RADAR

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RAIN / CLEAR AIR REFLECTIVITY

ATMOSPHERIC TURBULENCE

$$\eta(\lambda) = 0.38 C_n^2 \lambda^{-1/3}$$

$C_n^2 \text{ (m}^{-2/3}\text{)} \propto \text{turbulence}$
of refractive index

$$10^{-19} \text{m}^{-2/3} < C_n^2 < 10^{-13} \text{m}^{-2/3}$$

↓
turbulence
threshold

↓
strong
turbulence

HYDROMETEORES

$$\eta(\lambda) = 0.93 \pi^{5/\lambda^4} Z_e$$

$Z_e \text{ (mm}^6\text{/m}^3\text{)} \propto \text{precipitation}$
rate

$$0 \text{dBz} < Z_e < 50 \text{dBz}$$

↓ ↓
0,05 mm/h 100mm/h

$$Z_e = 1.34 \cdot 10^{15} C_n^2 \lambda^{11/3}$$



RELATIONSHIP BETWEEN EQUIVALENT REFLECTIVITY AND C_N^2 (IN COLOR), VERSUS RADAR WAVELENGTH

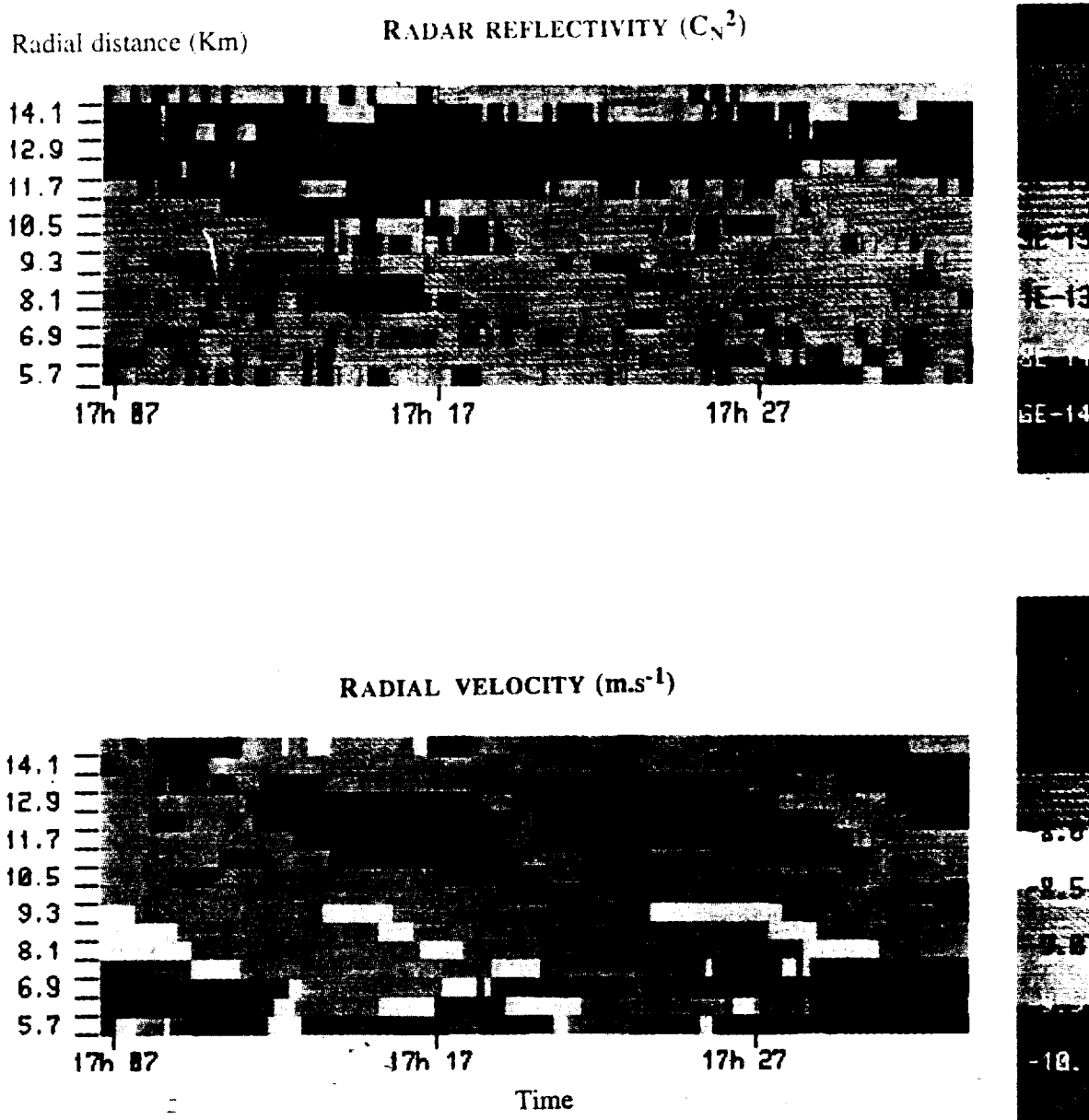
EXPERIMENTAL RESULTS WITH PROUST RADAR

METEOROLOGICAL CONDITIONS

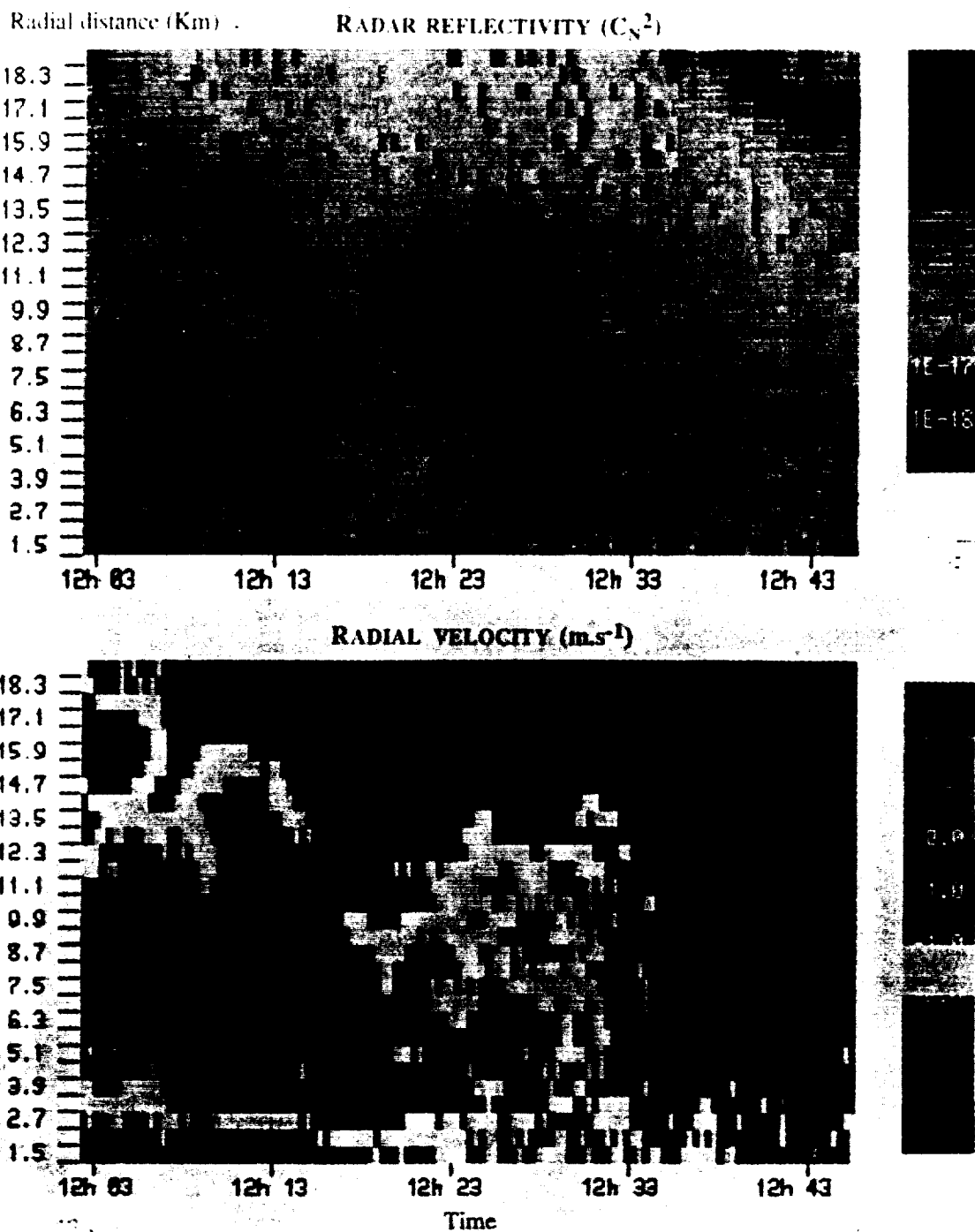
- CLEAR AIR

- CLOUDS

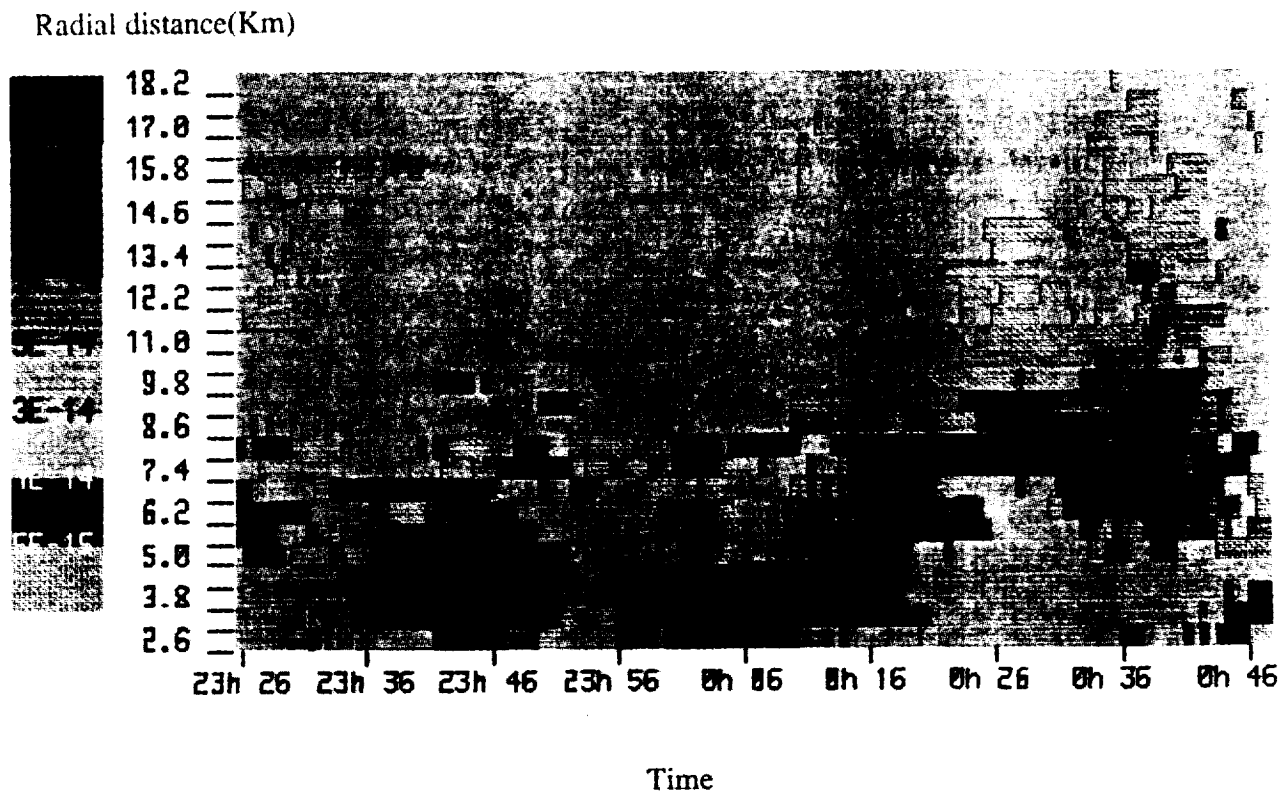
- RAIN



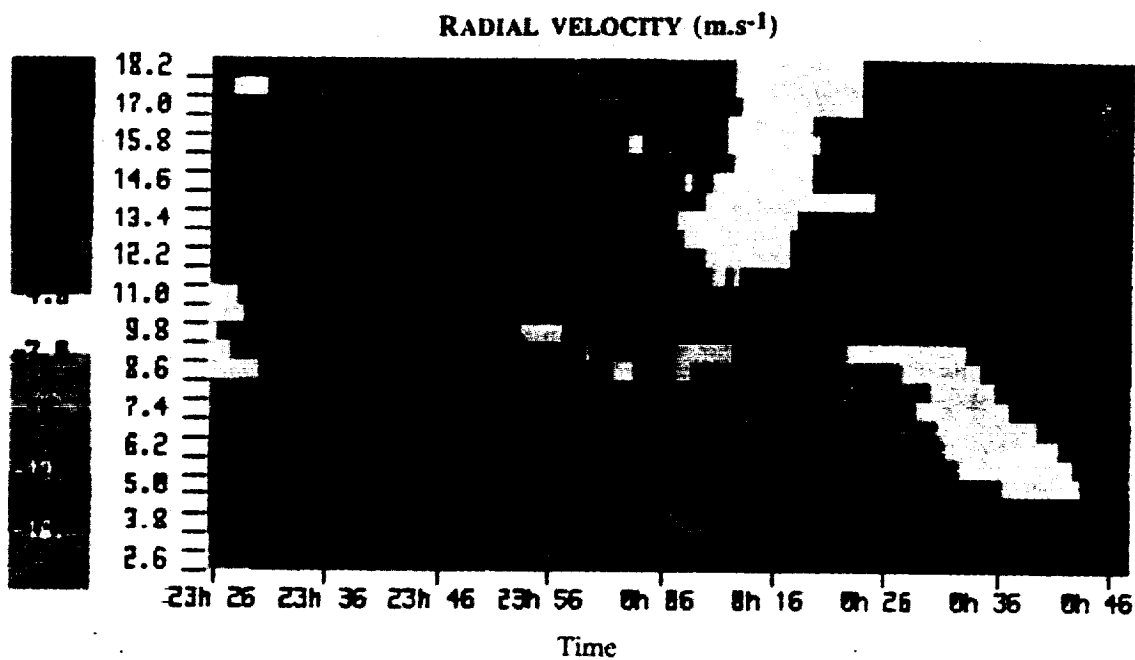
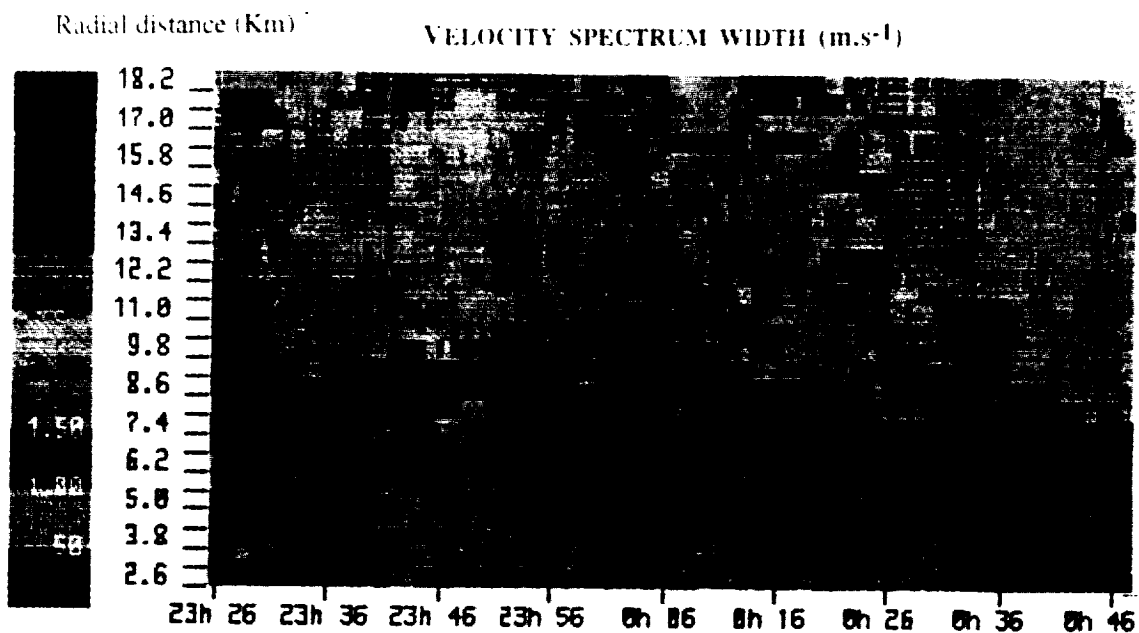
Radar reflectivity and radial velocity measured by PROUST radar in clear air at Coulommiers airport



PROUST radar observation of clouds (Cu). The clouds contours are well defined by the radar reflectivity

RADAR REFLECTIVITY (C_N^2)

Radar reflectivity measured by PROUST radar in
Coulommiers airport during a gust front



Velocity spectrum width and radial velocity obtained by
PROUST radar in Coulommiers airport during a gust front

CONCLUSION

Experimental results have shown the capability of 30 cm wavelength PROUST radar to detect low level wind shears in all meteorological conditions (from - 20 DBZ clear air echoes to heavy rain).

But there some limitations consisting essentially in the time resolution which is at least 5 s and the sensibility to ground clutter limiting the low elevation.

The comparison of its capabilities with those of 5 cm wavelength RONSARD radar which is less affected by ground clutter echoes will permit to select the best candidate.

N 9 1 - 2 4 1 6 9

Wind Shear Program in France

MEGASODAR Experiment
Alain Donzier, REMTECH

SODAR APPLICATION TO WIND SHEAR AND WAKE VORTEX DETECTION

A preliminary experiment supported by the French Civil Aviation has proven that wind measurement at low elevation angles using acoustic remote sensing was feasible. This experiment was conducted using a 2.4 meters parabolic dish antenna with about 2 watt of acoustic power emitted at 4000 Hz. The elevation angle was of 6 degrees.

However a reflector type antenna does not allow the antenna pattern optimisation that can be achieved on phased array type antennas. Moreover arraying elements increases the emitted power.

Remtech has recently developped a commercial phased array Sodar line. A 2 meters by 2 meters 432 elements commercial phased array system was operated at Roissy International Airport for a few days. You will find some radial wind data at the end of this document. Eventhough this system was not optimized for such application it showed ranges of about 800 meters for an averaging time of 10 minutes and an elevation angle of 20 degrees. Some strong echo regions are present in the data and seem to be related to wake vortex.

Further developments starting before the end of this year include :

- installation of an optimized phased array system at Roissy International Airport.
- gathering data for wake vortex study
- generalization of the signal coding techniques to reduce the acquisition time to a few minutes.
- beam steering with simultaneous measurement on 4 beams.

The study will allow the definition of the technical specifications of a system for wind shear and wake vortex detection having a range of at least two miles.

Wind Shear Program in France - Questions and Answers

Q: ERIC PALMER (McDonnell Douglas, Long Beach) - Has the DGAC/JAA a plan to require airborne wind shear systems? If so, what will be required and when?

A: BERNARD ADES (DGAC) - There is no requirement on the operational side yet; still waiting for more information on the phenomenon (characteristics in France and Europe). If a requirement is made, it shall be made in conjunction, in coordination, within a European Joint Airworthiness Authority rather than DGAC alone. Furthermore this would be made within the regular consultation, JAA/FAA consulting process.

Q: MARILYN WILSON (MIT Lincoln Laboratory) - Is wind shear a major hazard in France? Is it common?

A: BERNARD ADES (DGAC) - Not really. We've asked for a meteorological study to characterize the phenomenon in France. Unfortunately it has been very difficult to get data from the airport so what we've begun to do is to collect data from the nuclear centers where there is a strict follow up of the meteorological conditions. But yet we have no result from this study. We have very particular cases where kinds of wind shears were recorded in France, particularly south of France around Nice Airport, but it is something very rare. You see the problem is that our planes are still flying to other parts of Europe and also to the US.

Session II. Case Study

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Session II. Case Study

N91-24170

Integrated Data Analysis of July 7, 1990 Microburst
Dave Hinton, NASA Langley

ANALYSIS OF JULY 7, 1990 MICROBURST ENCOUNTER AT ORLANDO, FLORIDA

**DAVID A. HINTON
NASA, LANGLEY RESEARCH CENTER**

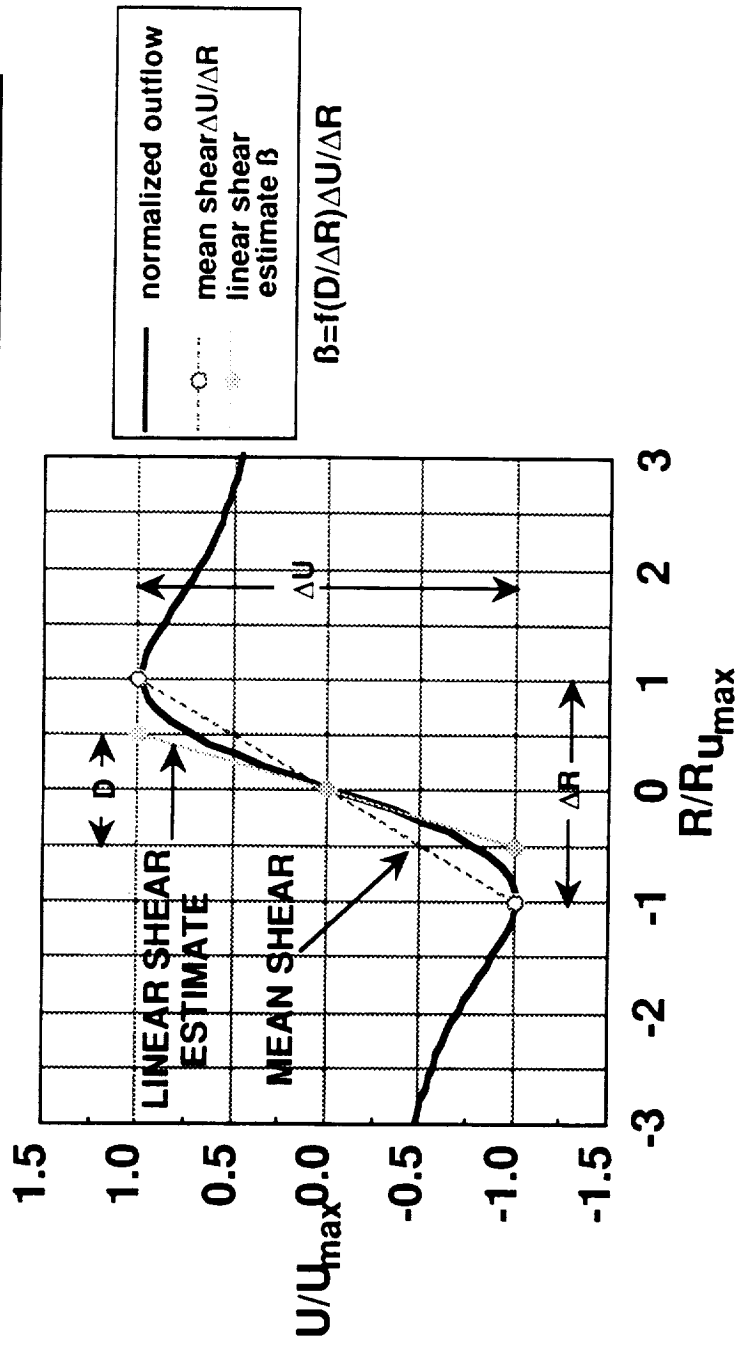
**THIRD COMBINED MANUFACTURERS' AND TECHNOLOGISTS'
AIRBORNE WINDSHEAR REVIEW MEETING
Hampton, VA**

Oct.16 - 18 1990

SUMMER 1990 TDWR FLIGHT EXPERIMENT

- INITIAL EFFORT IN INTEGRATION OF GROUND-BASED WINDSHEAR INFORMATION ON THE FLIGHT DECK
- EVALUATE NASA ALGORITHM FOR ESTIMATION OF MICROBURST F-FACTOR FROM TDWR DATA
- UTILIZE EXISTING RESOURCES AT ORLANDO
 - MIT LINCOLN LAB TDWR
 - UNIVERSITY OF NORTH DAKOTA CESSNA CITATION
 - TURBULENCE PREDICTION SYSTEMS INFRARED WINDSHEAR SYSTEM
- CORRELATE TDWR, AIRCRAFT IN SITU, AND INFRARED WINDSHEAR DATA

LEAST SQUARE ESTIMATE OF LINEAR SHEAR



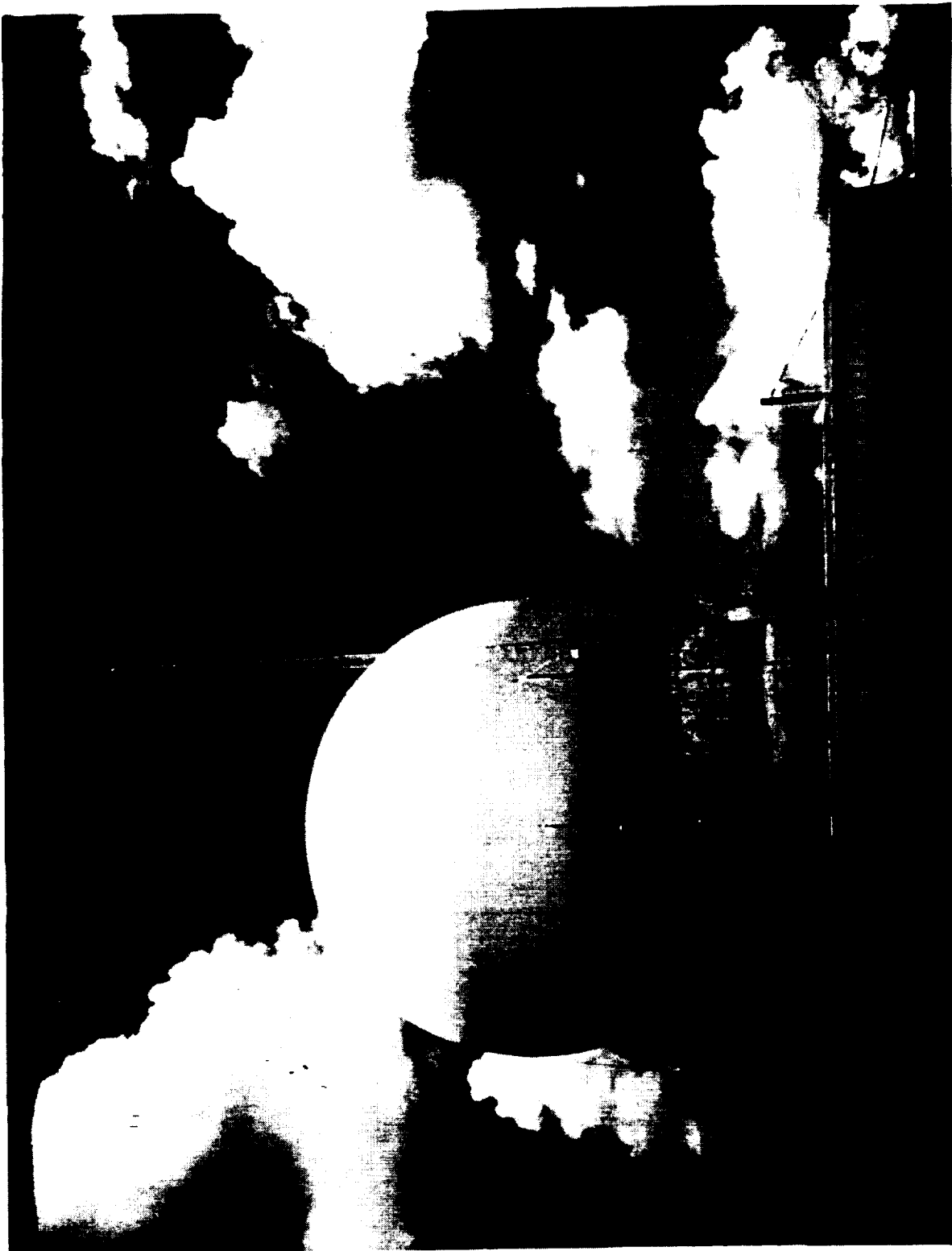
$$\beta = 4.1925 \frac{\Delta U}{\Delta R} \left[\left(\frac{\Delta R}{D} \right)^2 - \left(\frac{\Delta R}{D} \right)^3 \frac{\sqrt{\pi}}{2.2424} \operatorname{erf} \left(1.1212 \frac{D}{\Delta R} \right) \right]$$

$$F = \beta \left[\frac{V}{g} + \frac{2h}{V} \right]$$

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NASA



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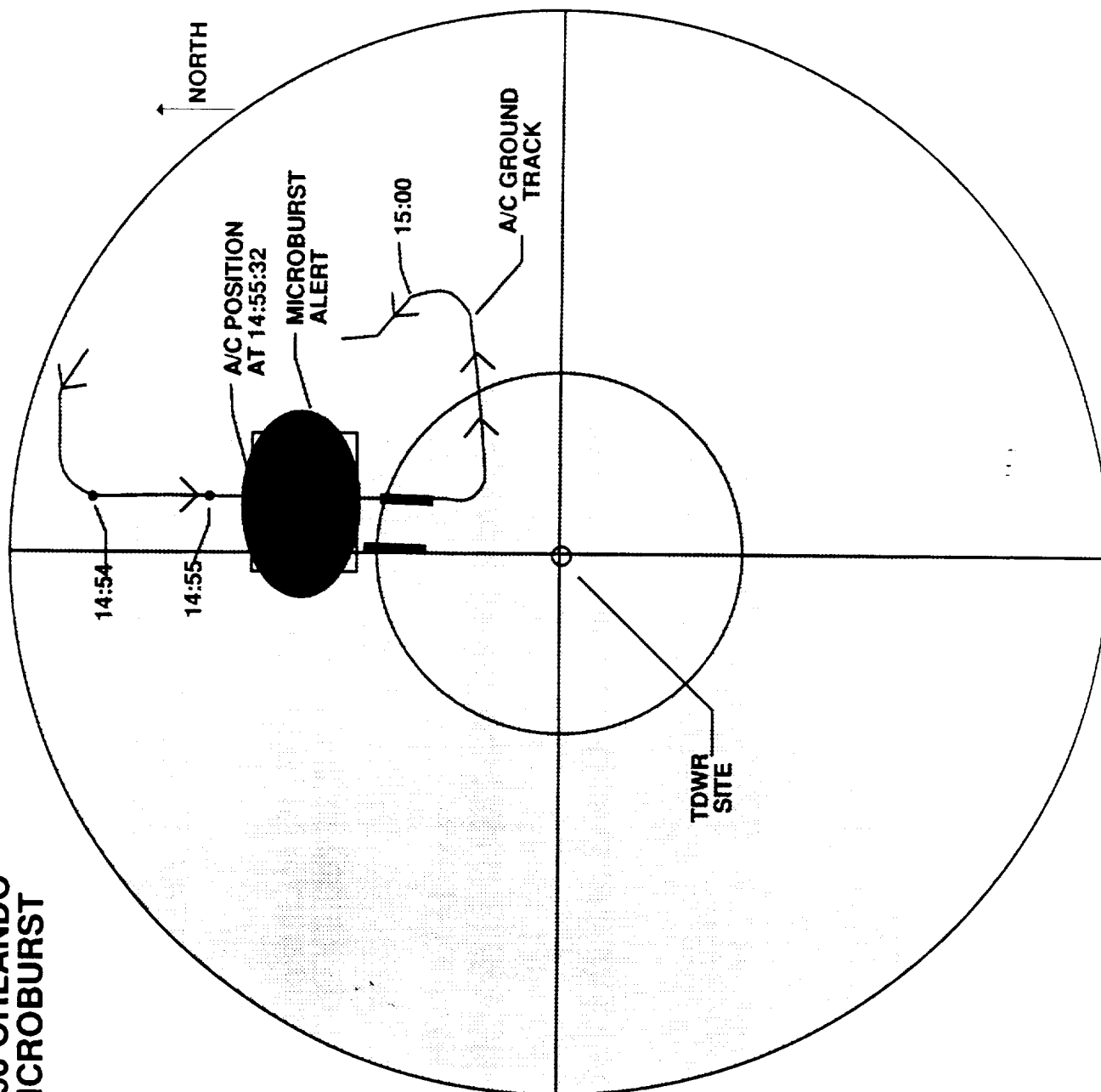
NASA



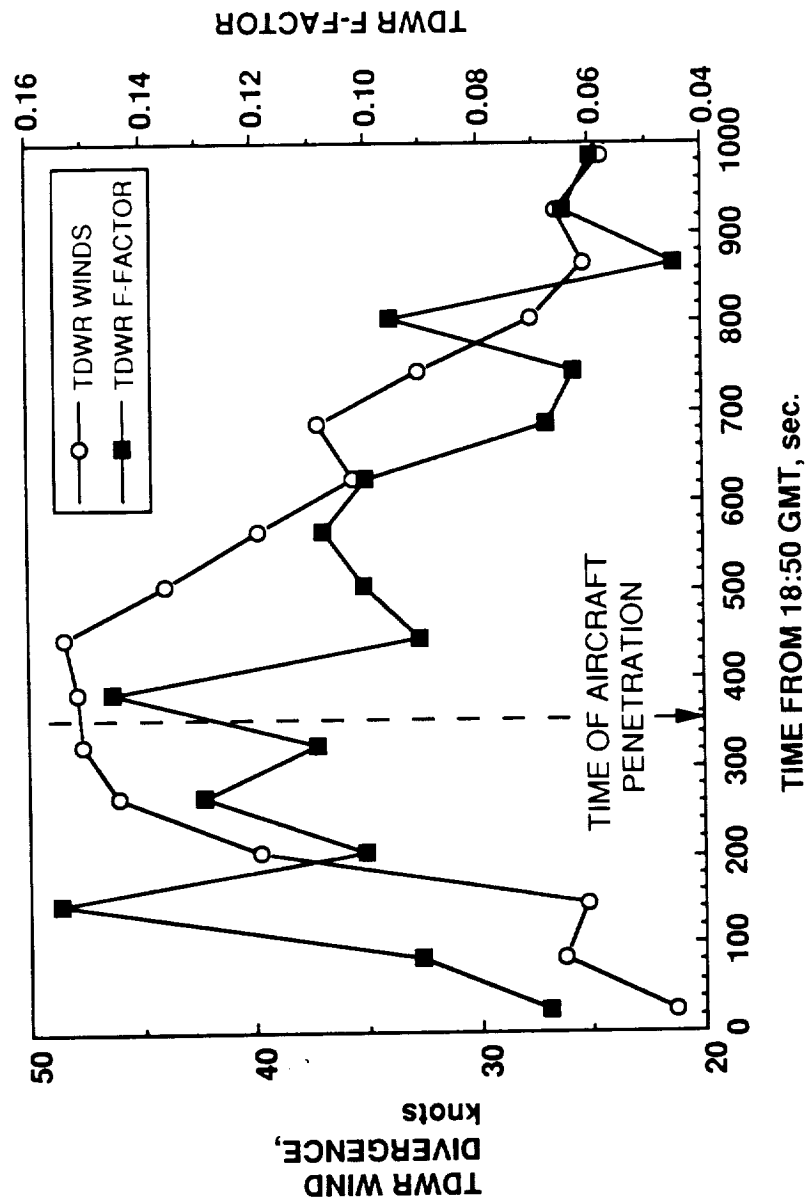
EVENT SYNOPSIS

- AT ABOUT 18:49 GMT, TDWR DETECTED A 60 DBZ ECHO AND 5 M/S DIVERGENCE ON APPROACH PATH TO RUNWAY 17L
- CITATION WAS AIRBORNE AND MANEUVERED FOR MICROBURST PENETRATION
- MICROBURST STRENGTH INCREASED RAPIDLY TO 25 M/S DIVERGENCE
- CITATION ROLLED OUT ON FINAL APPROACH 70 SECONDS BEFORE RAINSHAFT ENTRY
- CITATION PENETRATED CORE OF MICROBURST AT 18:55 GMT NEAR PEAK STRENGTH OF MICROBURST, ON LOCALIZER AND GLIDESLOPE
- CORRELATION POSSIBLE BETWEEN TDWR, INFRARED, AND AIRCRAFT IN SITU MEASUREMENTS OF THE EVENT

7/7/90 ORLANDO MICROBURST

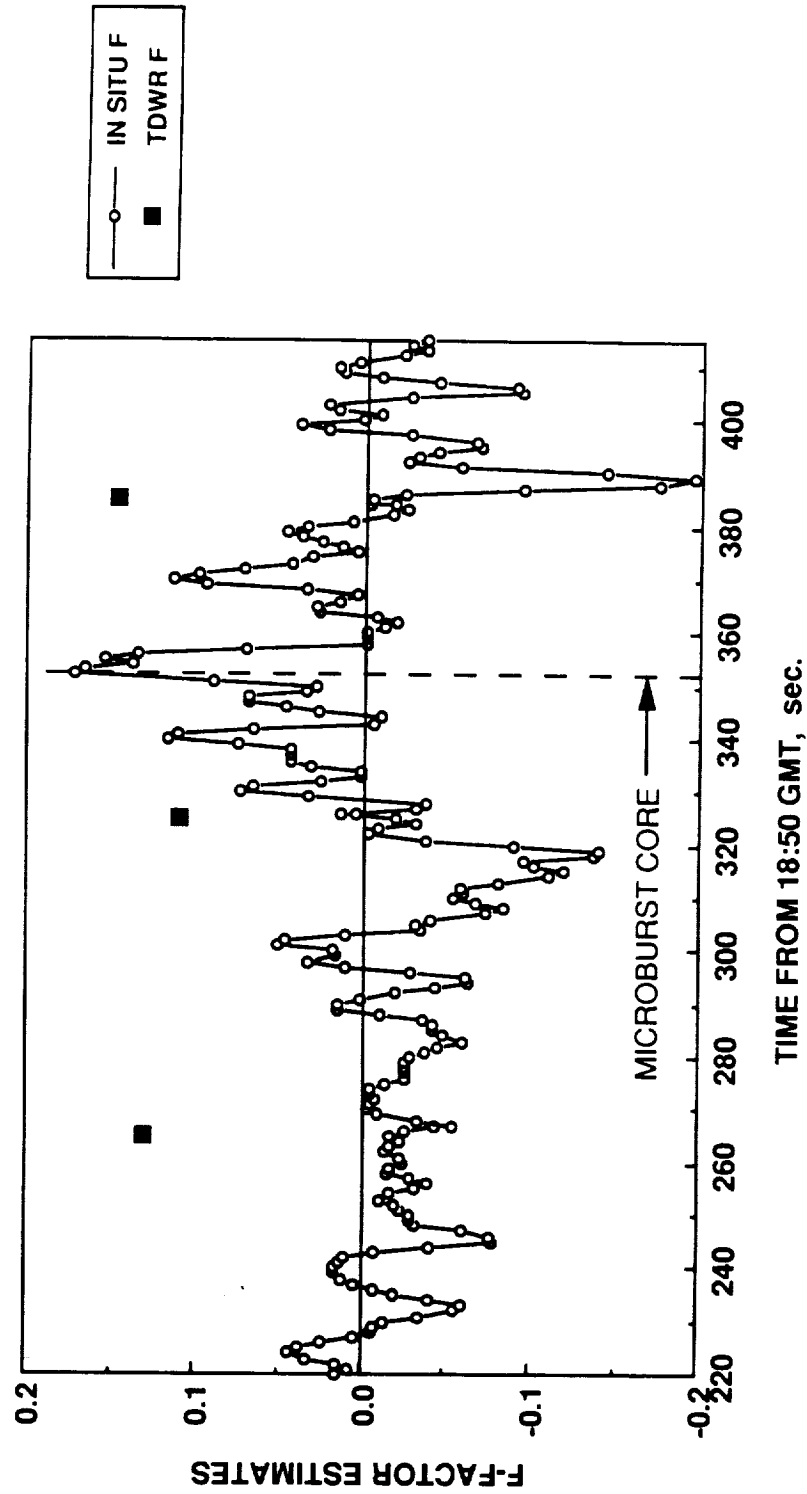


TDWR DATA ANALYSIS



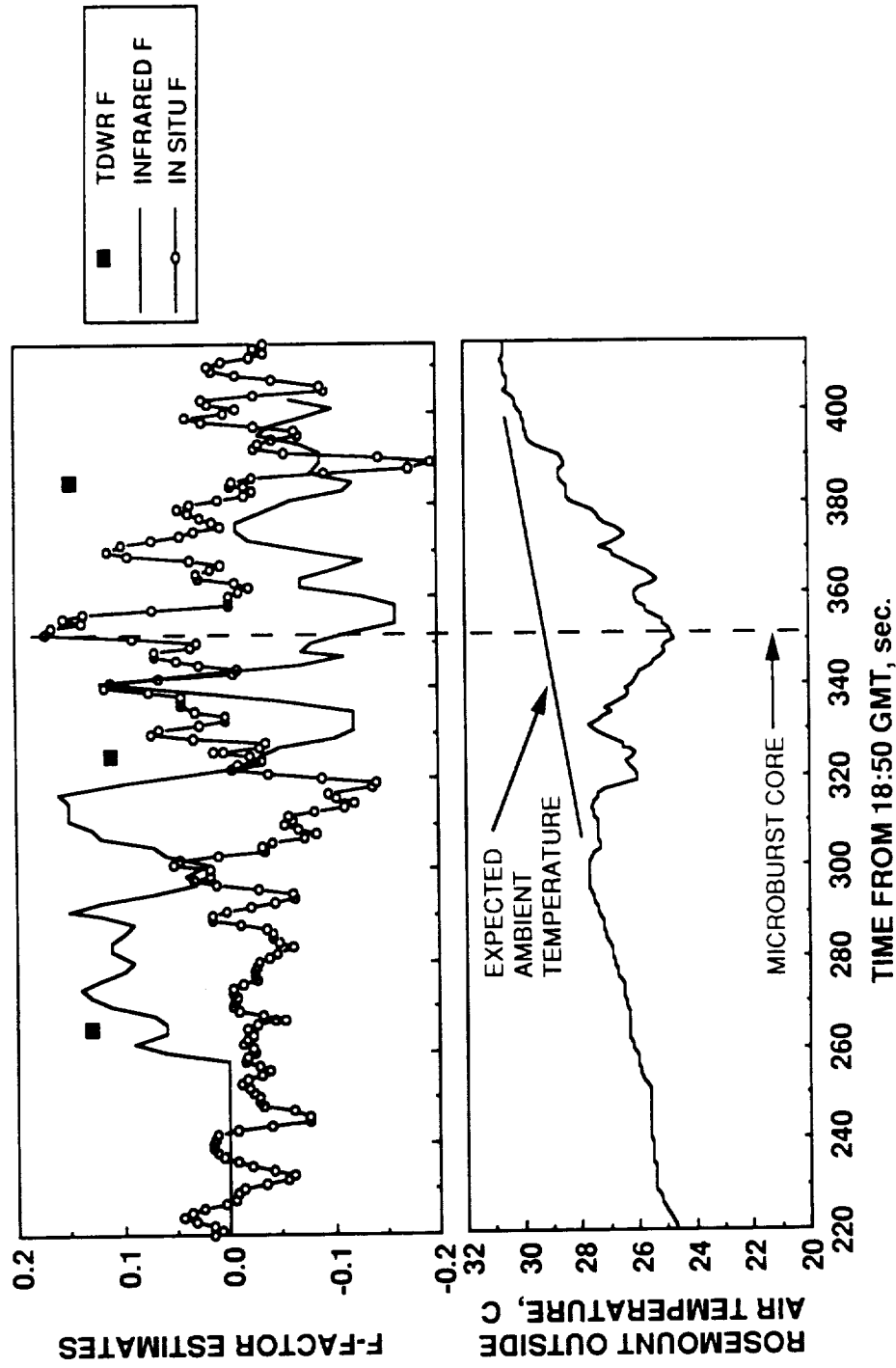
- PEAK DIVERGENCE WAS NEARLY 50 KNOTS (25 M/S)
- PEAK F-FACTOR ESTIMATE WAS 0.15
- F-FACTOR REMAINED ABOVE 0.10 FOR 5 MINUTES

CITATION AIRCRAFT IN SITU DATA ANALYSIS



- F-FACTOR CALCULATED FROM AIRCRAFT RECORDING OF WIND SPEED AND DIRECTION, AIRCRAFT TRACK, AND VERTICAL WIND
- PEAK IN SITU F-FACTOR WAS 0.17, RANGED FROM 0.13 TO 0.16 FOR 4 MORE SECONDS

INFRARED DATA ANALYSIS



- MICROBURST PRODUCED AN IN SITU TEMPERATURE DROP OF ABOUT 4°C
- PEAK INFRARED F-FACTOR WAS 0.16
- INFRARED PROVIDED LEAD TIME OF ABOUT 40 SECONDS

SUMMARY OF JULY 7 EVENT

- **SINGLE EVENT SAMPLED BY TDWR, INFRARED, AND AIRCRAFT IN SITU**
- **EXCELLENT CORRELATION OF THE THREE F-FACTOR ESTIMATES**
- **POSSIBLY THE FIRST AIRBORNE FORWARD-LOOK MEASUREMENT OF MICROBURST WINDSHEAR HAZARD VALIDATED BY AIRCRAFT IN SITU DATA**
- **ANALYSIS OF OTHER EVENTS REQUIRED TO VALIDATE/REFINE TDWR F-FACTOR ALGORITHM**

Integrated Data Analysis of July 7, 1990 Microburst Questions and Answers

Q: FRED REMER (University of North Dakota) - How would the July 7, 1990 microburst in Orlando have affected a transport category aircraft on a stabilized approach?

A: DAVE HINTON (NASA Langley) - That microburst would have generated, or should have generated a valid alert had any transport aircraft flown through it with a reactive system. The strength of the microburst (with an F-factor of about 0.15 or 0.17, depending on which measurement you take) indicates that an aircraft could have easily recovered from it had the pilot initiated a missed approach. Had the pilot attempted to continue through to landing it would have been somewhat dangerous.

Q: UNKNOWN - You said that it would have generated a light or something from a reactive system. What reactive system are you talking about?

A: DAVE HINTON (NASA Langley) - I said, had a transport category aircraft penetrated that microburst and had such an aircraft been equipped with a reactive system it should have generated a valid alert. This aircraft did not have a reactive system on board.

UNKNOWN - They're not all the same.

DAVE HINTON (NASA Langley) - I realize that; but if they are functioning properly they should have generated an alert. The event was strong enough that the threshold agreed to by the industry was exceeded for some 5 or 6 seconds. There should have been an alert had any system gone through there.

UNKNOWN - I didn't know there was a threshold agreed to by the industry.

DAVE HINTON (NASA Langley) - TSOC117.

UNKNOWN - There are reactive systems out there that were put together long before the TSO came out.

DAVE HINTON (NASA Langley) - I realize that. The "national speed limit" was an F-factor of 0.15 some years ago. I believe most systems in the field, even the older ones are threshold at approximately 0.12 to 0.13, in that ball park. This exceeded that threshold.

ROLAND BOWLES (NASA Langley) - To my knowledge there has never been a case where a reactive system has been tested in a situation where an alert was given and there was independent measurement to confirm the validity of that alert. Now, I'm going to probably start an argument here. There's some people that will probably argue that. The key point is where an alert occurred with a reactive system for which there was independent confirmation; a different data measurement. Now we've had a lot of crews say, "yea, that was about right." But as many of the responses that you get on that side of it, you've got a lot of crews saying, "no way can I accept the validity of that alert." One of the things that we want to do at Denver is to test that hypothesis. There are some subtleties involved here. I'm sure the manufacturers are putting good systems out there, but I know of no program where an alert has been given by purposely testing it in an environment for which there's been independent measurement. In the Orlando case, we had an exceedance of 0.1 for 5 or 6 seconds. It is perfectly believable that the gust rejection filtering in a system could knock that amplitude down and stretch it out in such a way that we may not have gotten an

exceedance of 0.1. Maybe the Honeywell people can comment on that. It depends on whose system it is.

Q: PETER ECCLES (MITRE Corp.) - Aircraft configuration (engine out, load distribution, even pilot experience) would affect aircraft survivability. Given a smart computer which keeps account of aircraft configuration, a combination of F-factor with configuration would give a better idea of a probability of survival. Would you agree?

A: DAVE HINTON (NASA Langley) - I would say from a technical viewpoint, yes, that obviously keeping track of these parameters would give a better idea. I'm not sure that from an operational point of view it's realizable or even desirable. One point of reference is that TSOC117 there is only one threshold given for all aircraft and we know that various aircraft, given all engines, have different recovery performance characteristics.

PETER ECCLES (MITRE Corp.) - We're not particularly stuck with that TSO, I mean there could be other TSOs.

DAVE HINTON (NASA Langley) - I assume that's subject to modification.

Q: BOB ROLL (Lockheed Missiles & Space Co.) - Is the 4 to 6° C temperature drop unique to the microburst type situation or does that occur in every day situations, even in clear weather? Secondly, is there always a temperature drop when a wind shear hazard (not necessarily a microburst) occurs?

A: DAVE HINTON (NASA Langley) - To answer the first part about the temperature drop occurring, it's not unique to microbursts, we also see a temperature drops in gust fronts. Some early infrared detection work was dealing specifically with gust front detection. As far as those temperature changes occurring in other conditions, i.e., sea breeze fronts, temperature inversions, that's still an open question. The current research being conducted, that being the program that Pat Adamson is in with American Airlines on the MD80s and some of the research we will be conducting on our 737, is designed to answer that question. The answer to the second part about are we seeing a temperature drop when a wind shear hazard exists, I suppose I have to ask, how do you define a wind shear hazard? That is, are we only talking about microbursts, are we also trying to determine or detect other types of wind shears. If we look only at microbursts there is a very strong correlation, even a scaling factor between the temperature drop and the strength of the event. If you start looking at other events, sea breeze fronts, convective turbulence, we don't expect to see that temperature correlation. It's not clear that we need to detect those anyway. That's a question industry will have to answer.

MARILYN WILSON (MIT Lincoln Laboratory) - I just want to qualify that a little bit. Some microbursts are not associated with temperature drops at the surface. It depends on where in altitude you look. Aloft there may be a temperature drop, and a strong correlation as you say. But near the surface some microbursts are actually associated with temperature increases.

DAVE HINTON (NASA Langley) - We've seen that. Fred Proctor's model has been able to recreate those situations. It's not clear how often those conditions exist and how strong a microburst tends to be when you get that type of a temperature inversion in stable air. That is another question that has to be answered.

Q: WAYNE SAND (NCAR) - With 62 events penetrated, can we expect a detailed functional analysis of a look-ahead system? If so, when? And, do you always see a temperature deficit in the microburst?

A: DAVE HINTON (NASA Langley) - I would say that as far as the 62 events are concerned the primary emphasis of that study is on correlation of terminal Doppler weather radar based F-factor measurements or estimations with the insitu measurements of the airplane as it goes through. Another objective is the correlation of the infrared F. We plan to correlate that wherever it makes sense to do so. What I mean by that is, there is some penetrations where the aircraft is not stabilized far enough away from the event to give the infrared system a chance to look at it, simply because of the nature of the way the airplane was flown in those events. When will that analysis be completed? It's always dangerous to say when an analysis is going to be completed, as you know. This study is being conducted under contract by Lincoln Labs. The contract was signed very shortly before the data collection started. So, they were only able to recently hire their data processing person. As soon as they automate that data processing we expect to process all of the events as quickly as we can. The final report is due, roughly in the early winter, February, somewhere in that ball park.

Q: JOHN HANSMAN (MIT) - You said that you only have a limited number of cases where you had enough infrared line up on the thing to make a measurement. Is that an inherent limitation on infrared in the future?

A: DAVE HINTON (NASA Langley) - I think we're talking about an inherent limitation of any forward look system. You have to remember these systems are designed to protect transport category aircraft flying instrument approaches, or perhaps visual approaches. But this research aircraft is occasionally making radical maneuvers in order to catch a microburst before it dissipates.

Q: JOHN HANSMAN (MIT) - Does that imply that procedurally, in potential microburst cases with look ahead systems you're going to have to stabilize on the approach sufficiently far ahead of the threat region, and is that any further out than the outer marker?

A: DAVE HINTON (NASA Langley) - No, I don't see that as further out than the outer marker.

A: DAVE HINTON (NASA Langley) - The third part of the question is, "do we always see the temperature drop?" Again I have to go back to the fact that we haven't seen the data yet. We haven't had a chance to look at the data from that experiment. I see that Pat would like to make a comment though.

PAT ADAMSON (Turbulence Prediction Systems) - We haven't actually analyzed the data, but looking at about 20 encounters on the UND aircraft, through the month of July or so, all of the downdrafts that we saw were associated with anywhere from about 3 to 7 degree temperature drops. Now those are all wet microbursts. We haven't reduced the Denver data and I don't know if we have a dry microburst there. So, we have a partial answer to your question. One of the things that we do see is a unique signature for a microburst. That's really where the differentiation comes between a gust front or a sea breeze or whatever, is in the unique signature of the microburst.

Q: ROB ROSEN (Hughes Aircraft Co.) - How far did the IR sensor see? Was the IR sensor scanning? Was the IR sensor able to estimate range and how accurately? Was it able to estimate the size and the slope of wind shear?

A: DAVE HINTON (NASA Langley) - The sensor was looking about 40 seconds ahead, which is approximately 2 nautical miles at 190 knots. Was the infrared scanning was the next part of the question. The answer to that is no, it's a fixed look point sensor. It's

actually looking at two elevations for various reasons but it's not a scanning in azimuth type situation. The third part, was the infrared sensor able to estimate range and how accurately? The answer to that is that the infrared sensor is not a ranging type instrument and it's not a range gaited instrument. It looks at two points, one very close to the airplane, the near temperature, and it looks at a second point relatively far, called the far temperature. It uses the difference in temperature and the rate of change of that difference to estimate an F-factor. You can call it pseudo ranging if you like because it varies with atmospheric humidity and rain. Pat would you like to add something to that?

PAT ADAMSON (Turbulence Prediction Systems) - We actually do calculate a look distance but it's probably only good to about 20% at best.

Q: DAVE HINTON (NASA Langley) - And it's not presented to the pilot?

A: PAT ADAMSON (Turbulence Prediction Systems) - Not at this time, it could be though but we don't give it out at this time.

A: DAVE HINTON (NASA Langley) - The fourth part of the question, "was it able to estimate the size and the slope of the wind shear?" The output of the infrared sensor is an F-factor estimate based on the scaling laws that have been derived using meteorological models such as Fred Proctor's and real world observations. Again, not being a ranging system it cannot estimate the physical extent of the microburst. It cannot tell you that it's a 1 or 2 or 3 kilometer diameter event. It can only tell you it's there, it's going to be approximately, depending on humidity, 30, 40 seconds in front of the airplane and give you an estimate of the F-factor based on the temperature change and the rate of change of that temperature.

Q: UNKNOWN - You mentioned that it gives us a 20 second warning, was there rain between the aircraft and all the way to 20 seconds in front of the aircraft?

A: DAVE HINTON (NASA Langley) - We're talking about 40 seconds here, not 20. No, the air was relatively dry and we had a very dense rain shaft. Pat Adamson has a video tape that I understand he's going to try and show Thursday which shows it very clearly. There was very good visibility, a good VFR flying day and a very well defined rain shaft associated with the microburst.

Q: SCOTT GRIFFITH (Allied Pilots Association/American Airlines) - Based on your event analysis, how well does the Turbulence Prediction Systems' predictive algorithm work as a reactive system, i.e., does the insitu measurement of delta T correlate well with the wind shear measurement?

A: DAVE HINTON (NASA Langley) - If I understand your question, is it based on a local measurement of F as opposed to a global measurement? People have asked us, "would you expect temperature changes while you're crossing a microburst to correlate to F-factor instantaneously?" We haven't seen the theoretical analysis of the physics that would suggest that's the case. We have always said we expect temperature to correlate extremely well or very well with the total F-factor of the shear but not to necessarily predict the performance increase going in or moment by moment what the F-factor is going to be. However, some of the data we've seen shows that there are correlations. I'm not sure exactly why. You saw in this case there was a performance increase predicted, and a performance decrease predicted. There were even some peaks in the insitu F-factor that could be traced to peaks in the temperature profile as the airplane was flying through and we have seen that in some model cases as well. Pat Adamson has something to add to that.

PAT ADAMSON (Turbulence Prediction Systems) - We've got the data from the infrared sensors and the insitu. The instrument actually receives the outside air temperature from the aircraft plus we have two detectors. For those who will be here on Thursday, I'll be showing that data. The insitu (the calculation of F from the aircraft sensor, the outside air temperature) on the citation calculated a 0.15 F-factor about 15 seconds prior to the insitu from the winds. So we have, if you will, two infrared and one local temperature sensor and with the algorithms we use they all calculated the hazard index within 0.02 of that which was experienced by the winds.

DAVE HINTON (NASA Langley) - To correct something I just said, the infrared detected a performance increasing shear on the far side of the microburst. It did not detect the performance increasing shear prior to getting in there. The reason is, there is no warming to correspond to predicting a negative F-factor. There is warming on the other side as you're exiting.

Session II. Case Study

N 9 1 - 2 4 1 7 1

Model Comparison of July 7, 1990 Microburst
Dr. Fred Proctor, MESO

THIRD COMBINED MANUFACTURERS' AND TECHNOLOGISTS'
AIRBORNE WIND SHEAR REVIEW MEETING

THREE DIMENSIONAL NUMERICAL SIMULATION OF THE 7 JULY 1990 ORLANDO MICROBURST

Fred H. Proctor
NASA Langley Contractor

October 16, 1990

7 JULY 1990 ORLANDO, FL SIMULATIONS

INPUT DATA / ASSUMPTIONS

**SOUNDING OBSERVED APPROX. 2 HRS BEFORE STORM (FROM
SPECIAL RAWINSONDE LAUNCH 1655Z)
LOW-LEVEL WINDS MODIFIED USING AIRCRAFT MEASUREMENTS
TAKEN NEAR THE TIME AND LOCATION OF THE STORM**

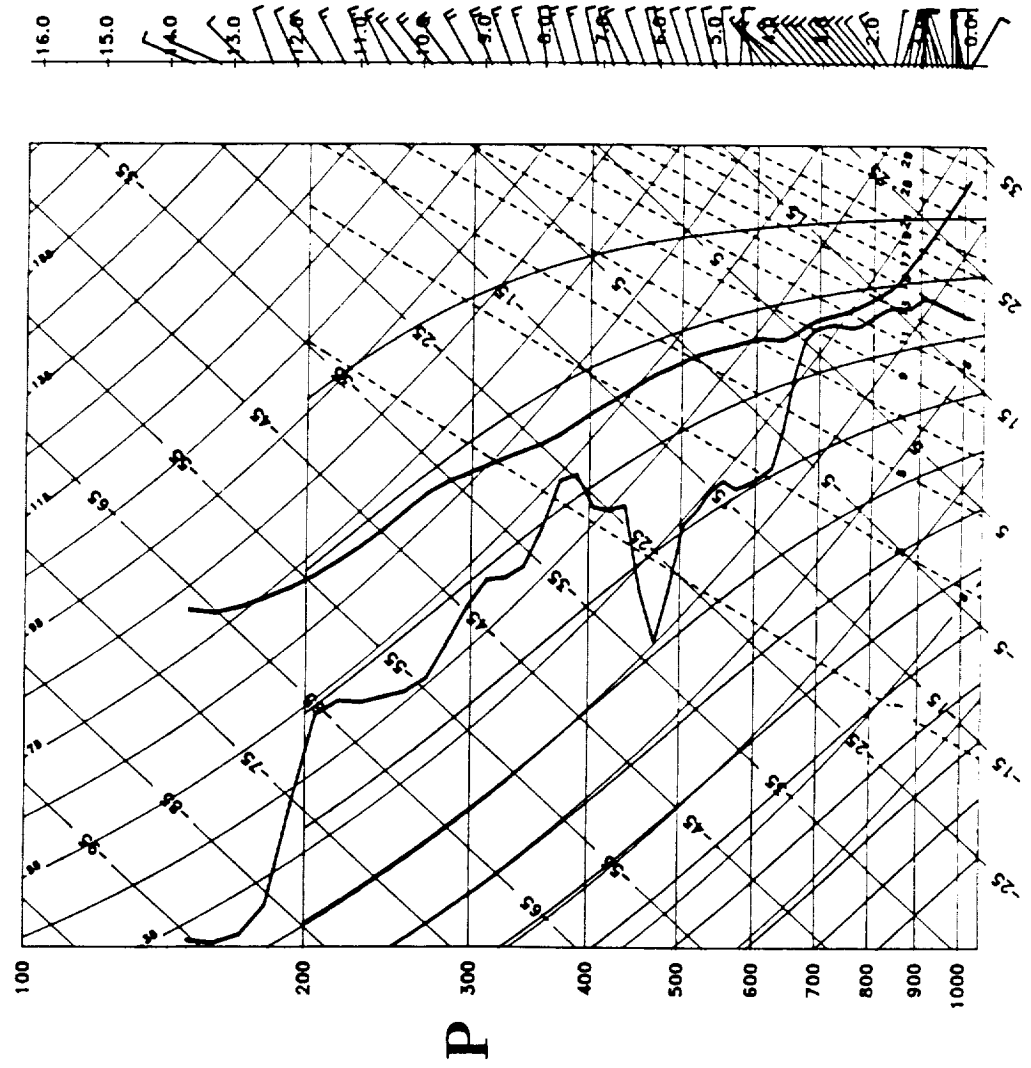
COMPUTATIONAL RESOLUTION

- HORIZONTAL - 125 M (103 X 103 GRID POINTS)**
- VERTICAL - 70 M NEAR GROUND STRETCHING TO 420 M AT 14 KM
(62 LEVELS)**

PHYSICAL DOMAIN SIZE

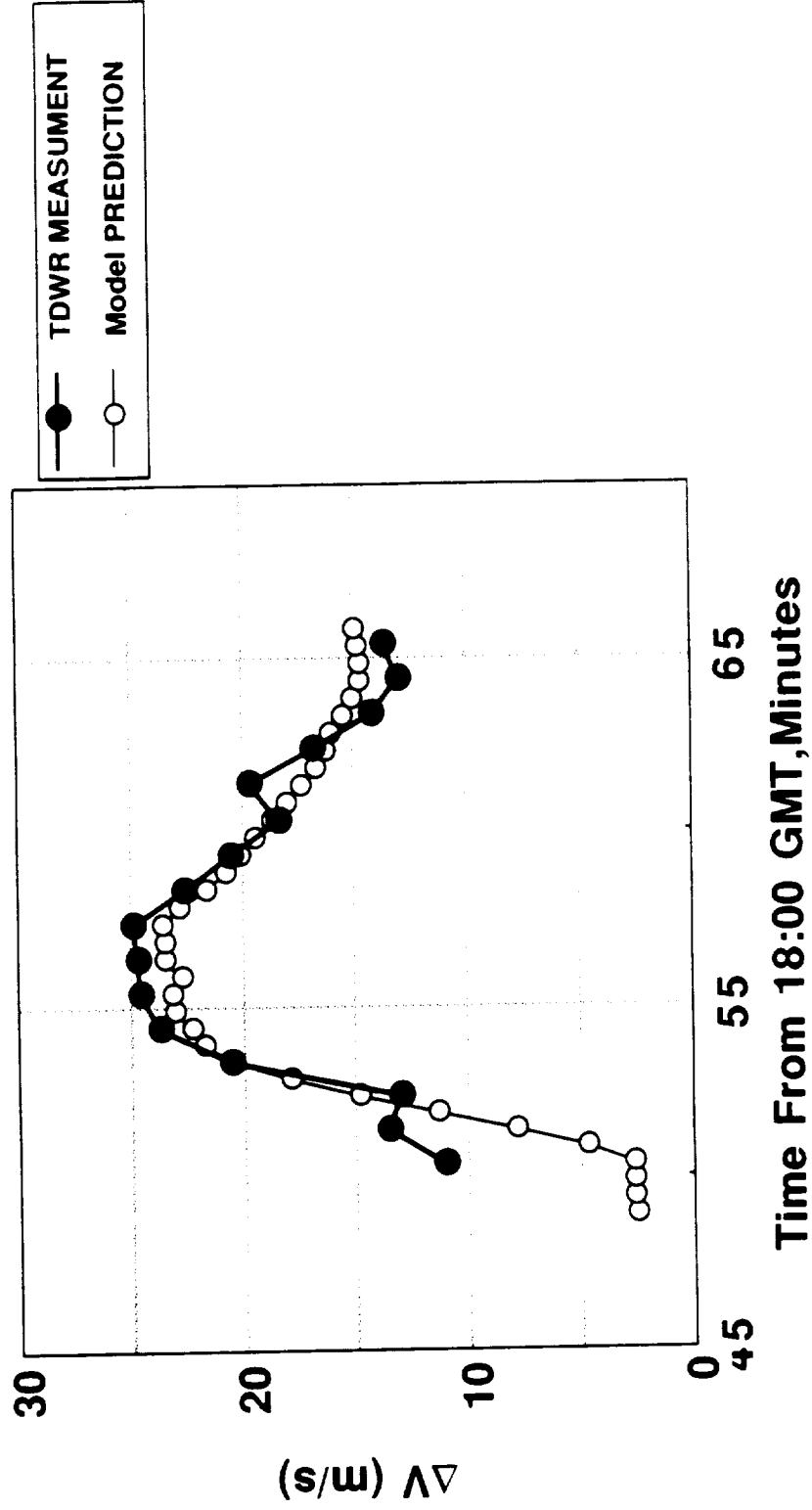
- SPHEROIDAL THERMAL IMPULSE**
- DIMENSIONS - 5 KM HORIZONTAL x 1.5 KM VERTICAL**
- AMPLITUDE - 1.5° C**

MODEL INPUT SOUNDING FOR 7 JULY 90 ORLANDO CASE



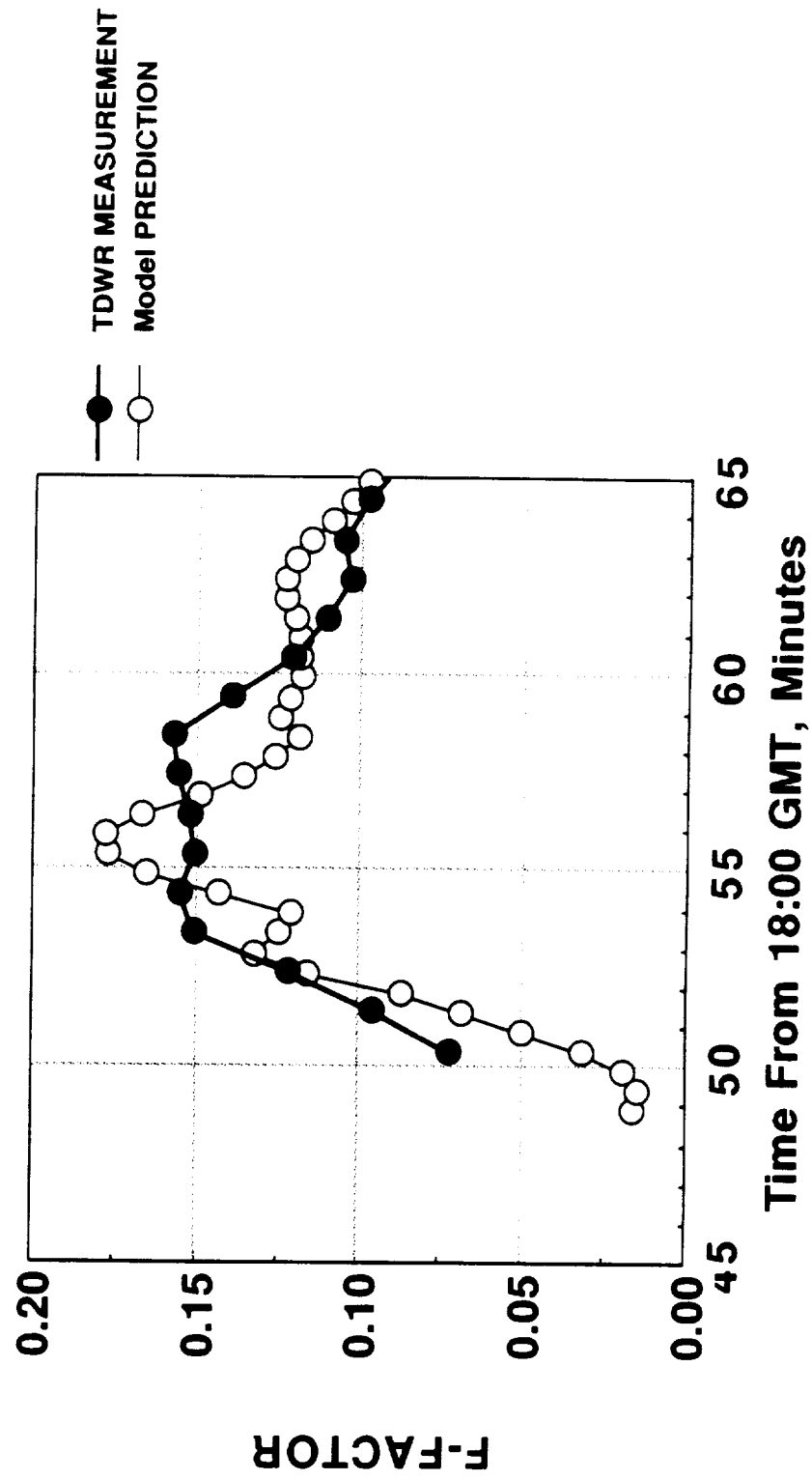
7 JULY 1990 ORLANDO MICROBURST

DIFFERENTIAL OUTFLOW COMPARISON BETWEEN DOPPLER RADAR DATA AND NASA MODEL SIMULATION



7 JULY 1990 ORLANDO MICROBURST

F-FACTOR COMPARISON BETWEEN DOPPLER RADRR DATA
AND NASA MODEL SIMULATION



COMPARISON OF SIMULATED AND OBSERVED CHARACTERISTICS OF MICROBURST EVENT

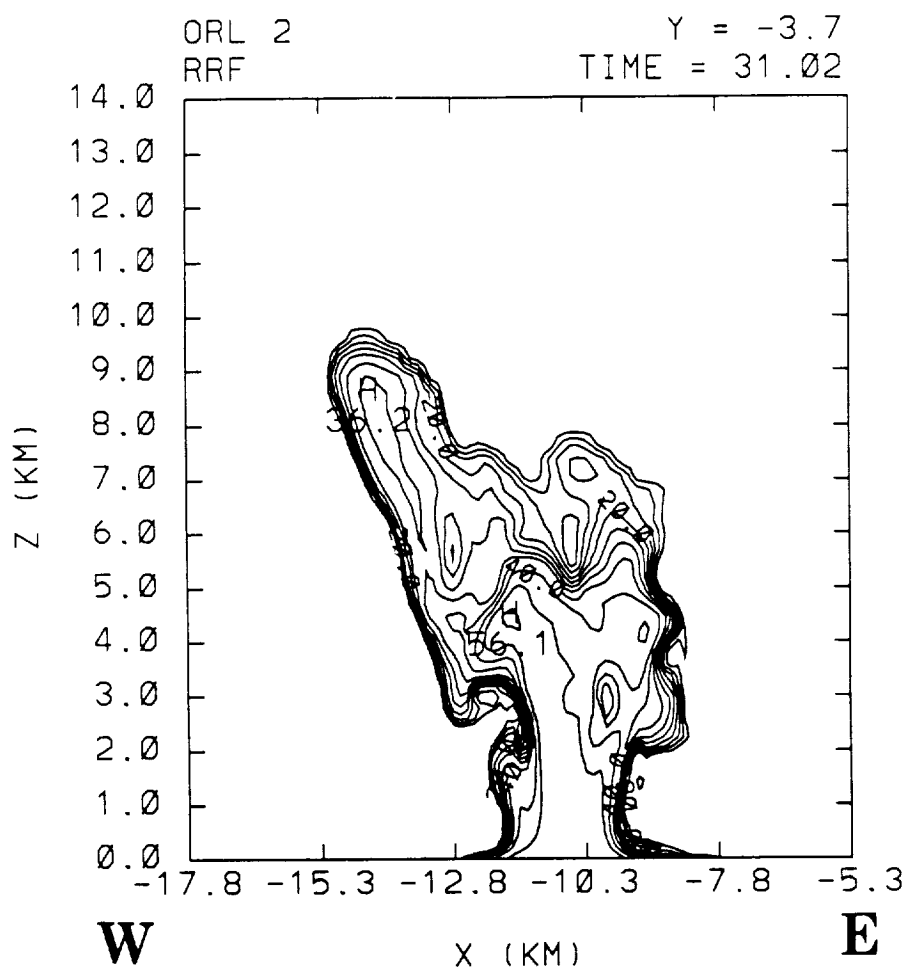
	SIMULATED	OBSERVED
MAXIMUM N-S DV	23.6 m/s at 1856:30	24.9 at 1857:25
MAXIMUM (1-km averaged) F-FACTOR	.178 at 1855	.168 at 1857:25
STORM TOP	10.5 km at 1857	10 km at 1855
PEAK RADAR REFLECTIVITY	57.6 dBZ at Z= 5 km & 1847	68 dBZ at Z = 5 km & 1846
PEAK RAINFALL RATE	5.64 in/hr at 1856	7.80 in/hr at 1857
MAXIMUM TEMPERATURE DROP	-10.4°C at 1900:30	-11.5°C at 1901

MODEL TIME CONVERSION
1850 GMT = 25 MIN MODEL TIME

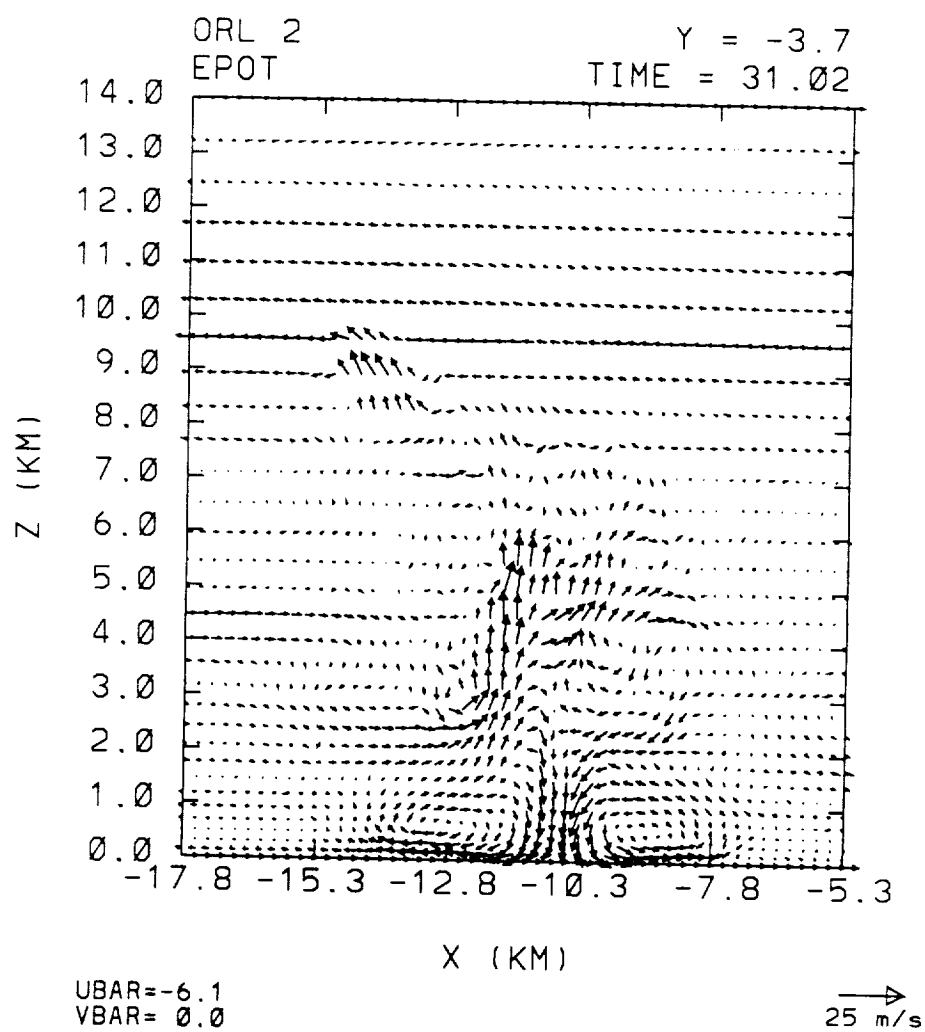
COMPARISON OF SIMULATED AND OBSERVED CHARACTERISTICS OF MICROBURST EVENT CONTINUED

	SIMULATED	OBSERVED
PEAK LOW-LEVEL WIND GUST	20.2 m/s at 1855	12 m/s at 1855
TIME PRECIPITATION FIRST MEASURED AT GROUND	1848:51	1848
STORM TRANSLATION 18:28 - 18:55 GMT	(u, v) = -6.1, -2.3 m/s	(u, v) = -7.4, -2.4 m/s

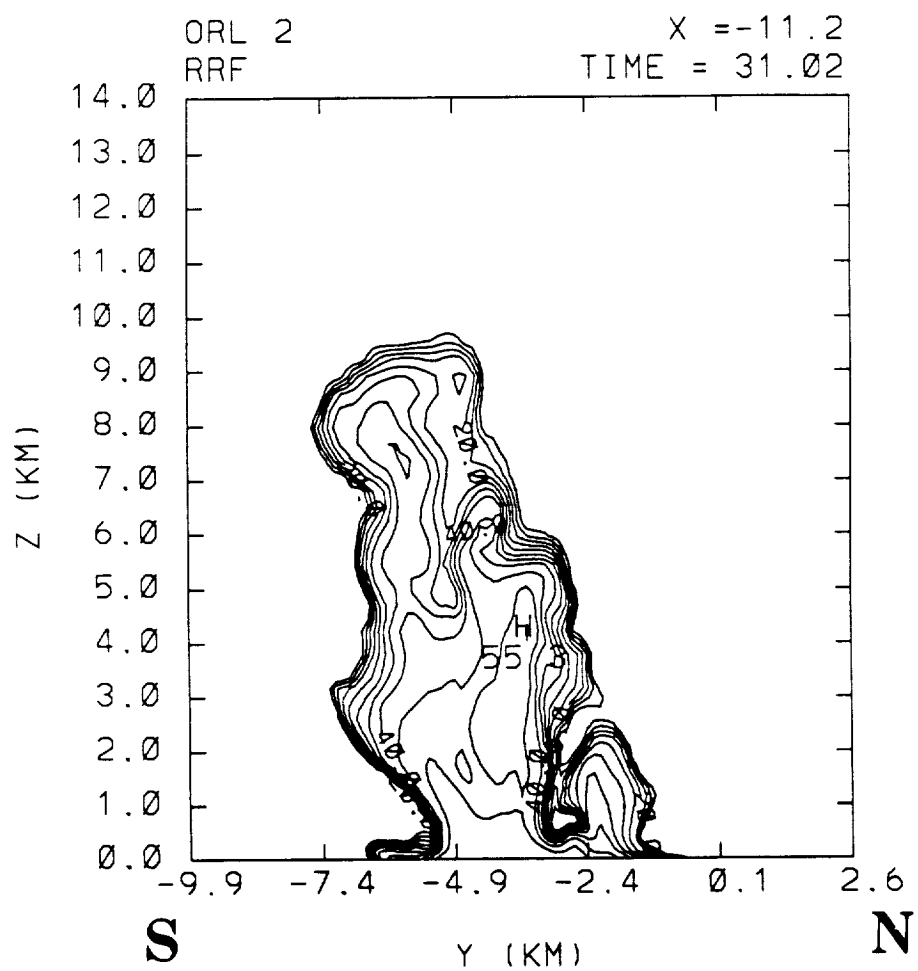
**MODEL TIME CONVERSION
1850 GMT = 25 MIN MODEL TIME**



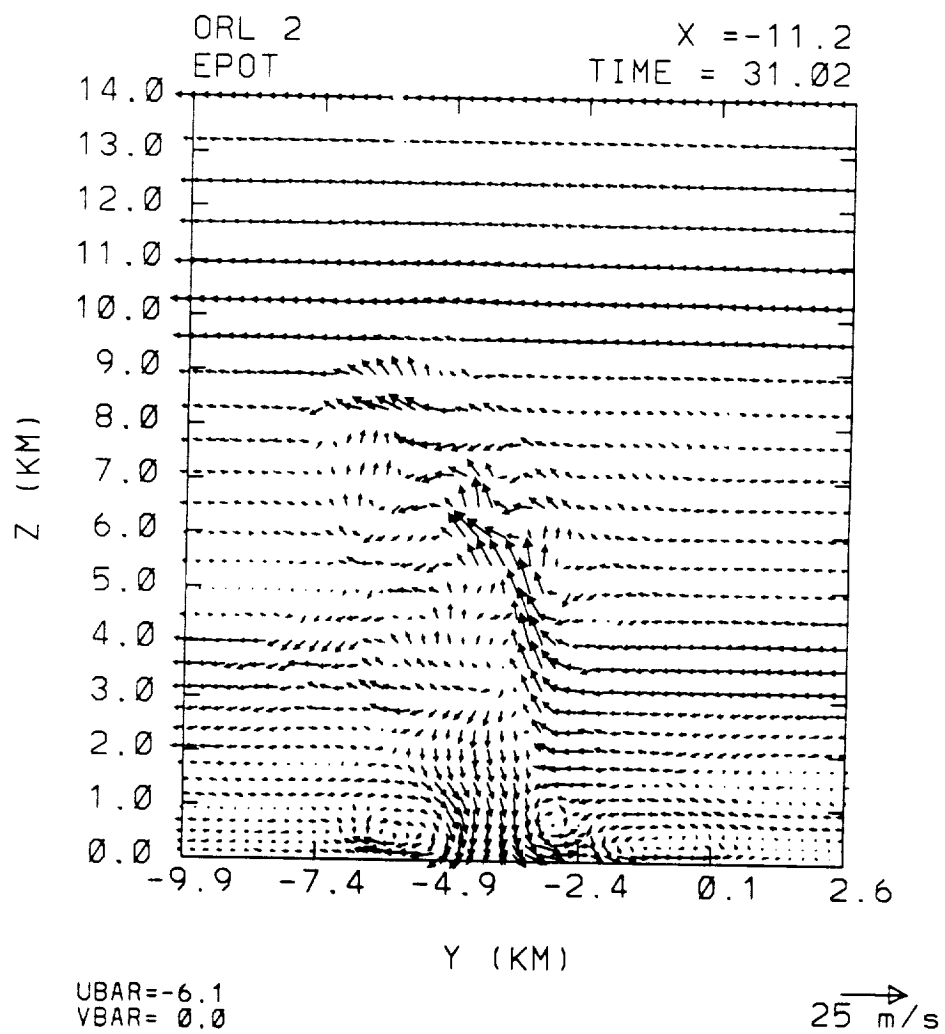
**SIMULATED EAST - WEST CROSS SECTION
RADAR REFLECTIVITY (CI = 5 dBZ)**



SIMULATED EAST-WEST CROSS- SECTION STORM RELATIVE WIND VECTOR



**SIMULATED NORTH - SOUTH CROSS SECTION
RADAR REFLECTIVITY (CI = 5 dBZ)**

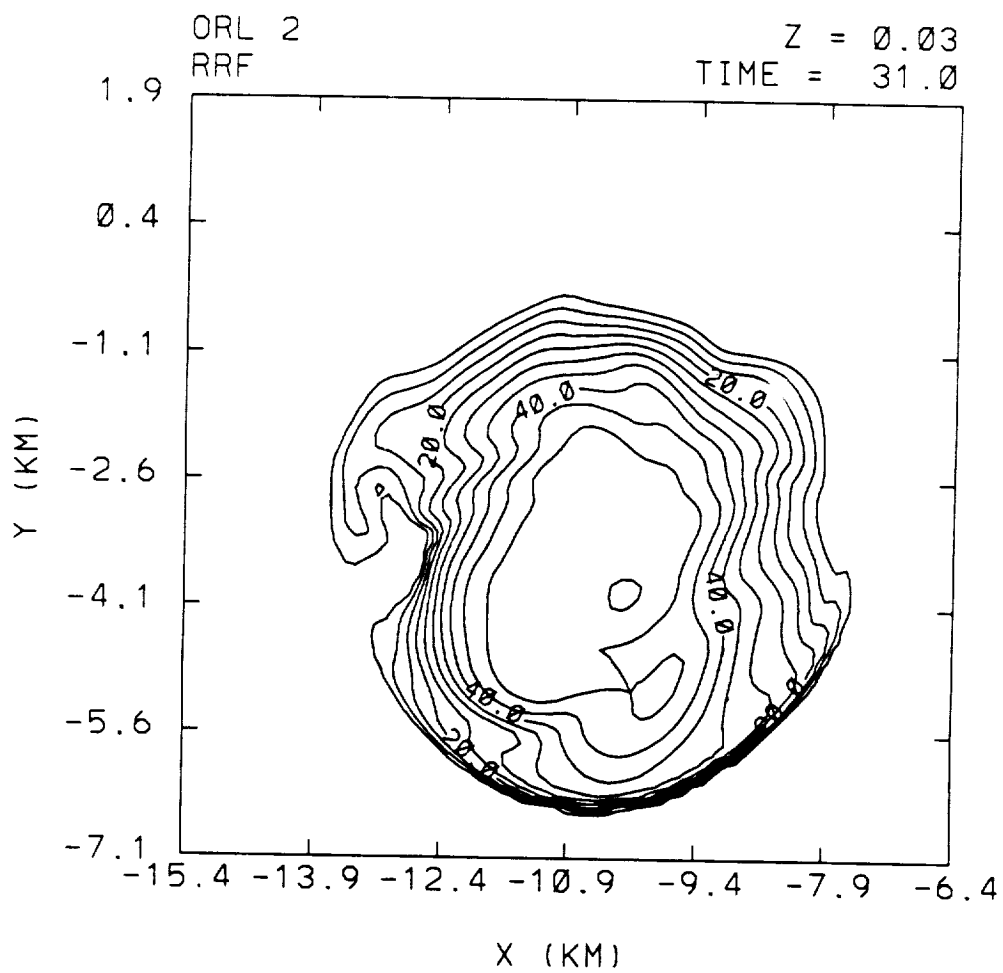


SIMULATED NORTH - SOUTH CROSS SECTION STORM RELATIVE WIND VECTORS

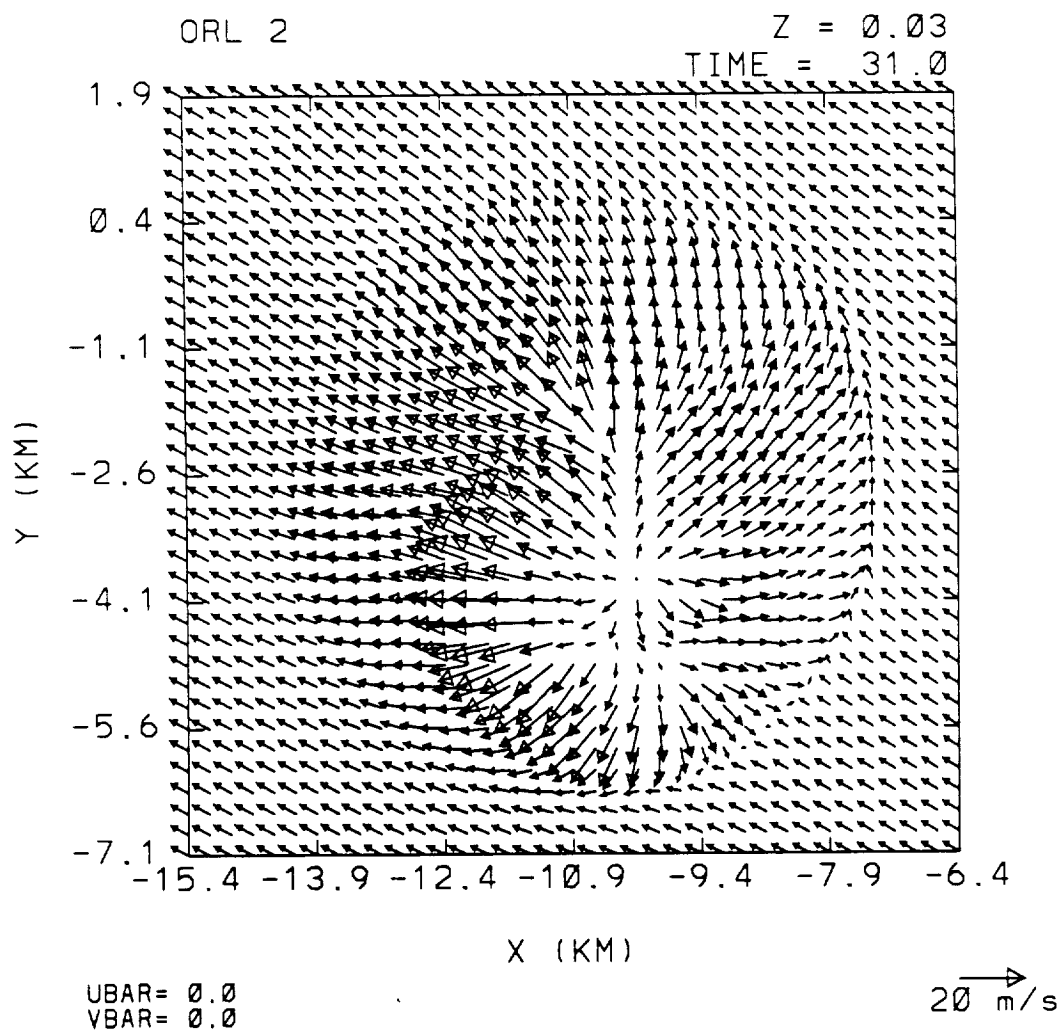
7 JULY 1990 ORLANDO MICROBURST SIMULATION

UNIQUE FEATURES

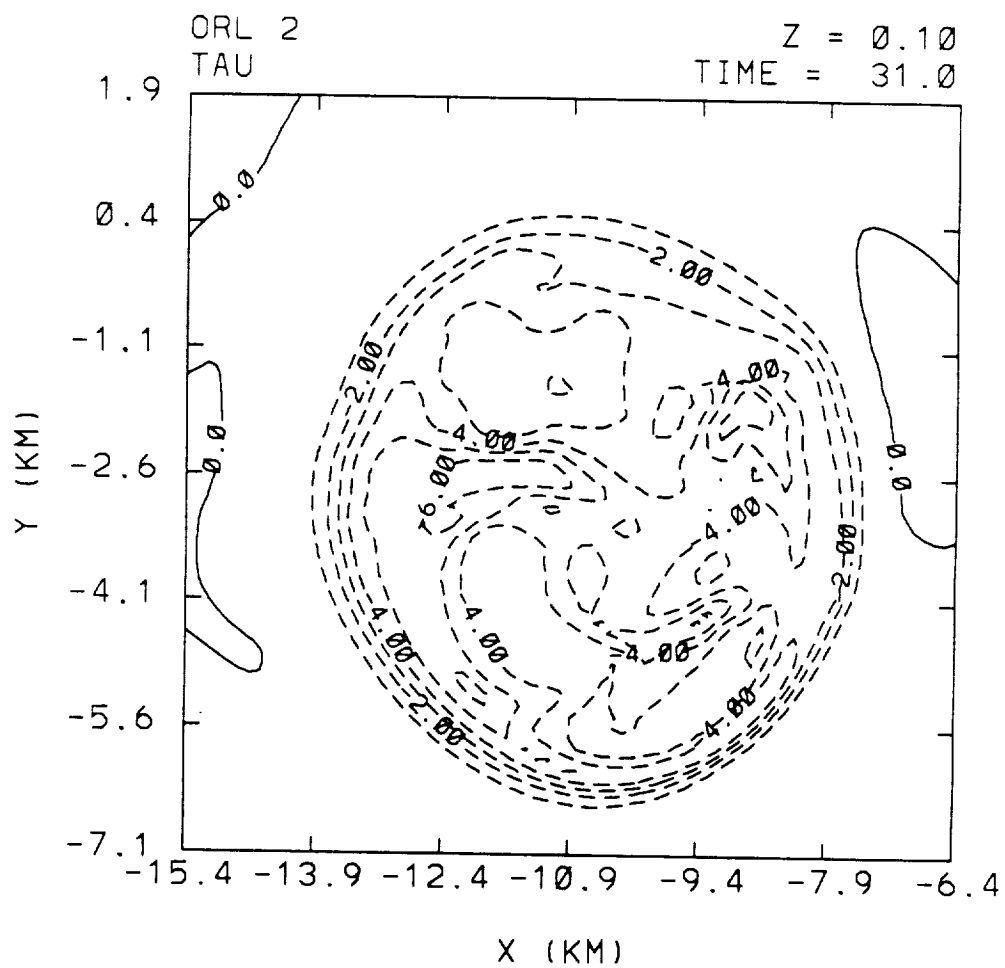
- O MULTIPLE DOWNDRAFT CENTERS
- 4 MAJOR CENTERS -**
- O NON CLASSIC F-FACTOR FIELD
- PERFORMANCE INCREASING AREAS
EMBEDDED WITHIN OUTFLOW
(CONFIRMED FROM AIRCRAFT) -**
- O F-FACTOR COMPUTED FROM PEAK ∇V
RESULTS IN UNDERESTIMATE**



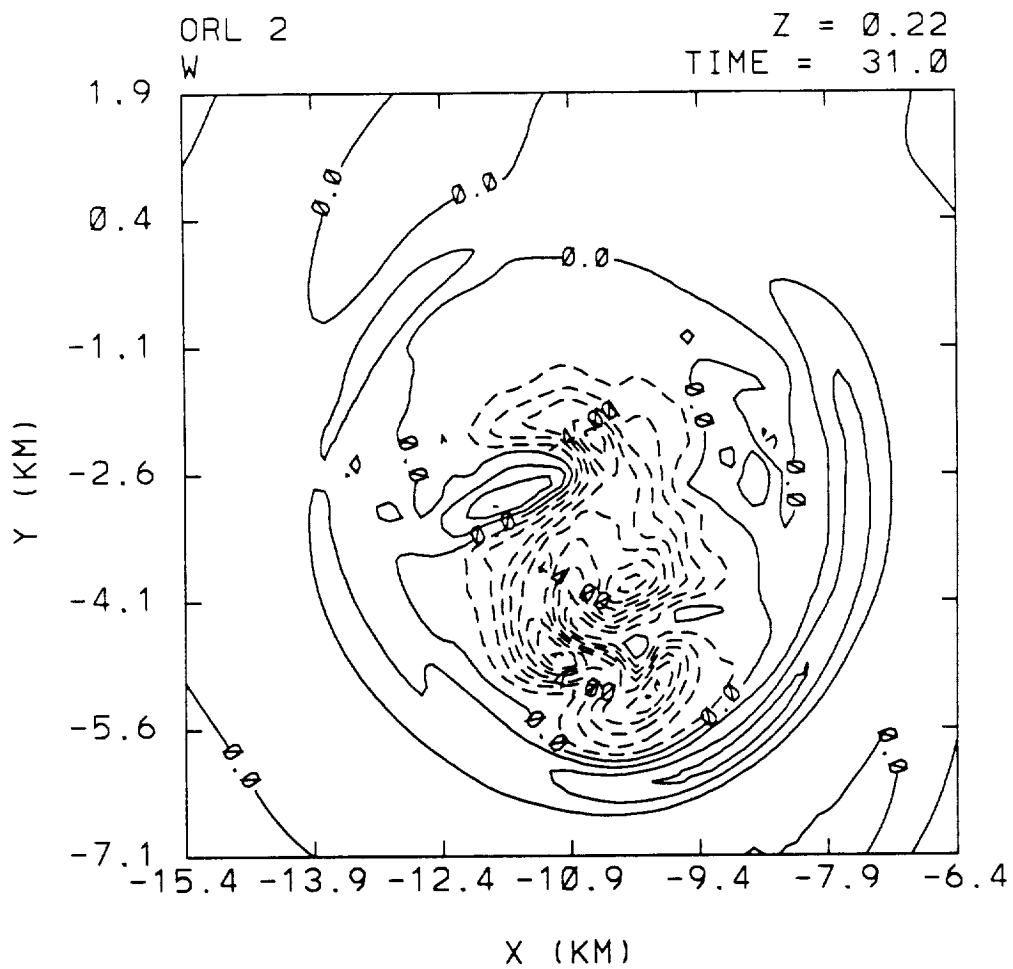
SIMULATED RADAR REFLECTIVITY AT 30 M AGL, CI = 5 DBZ



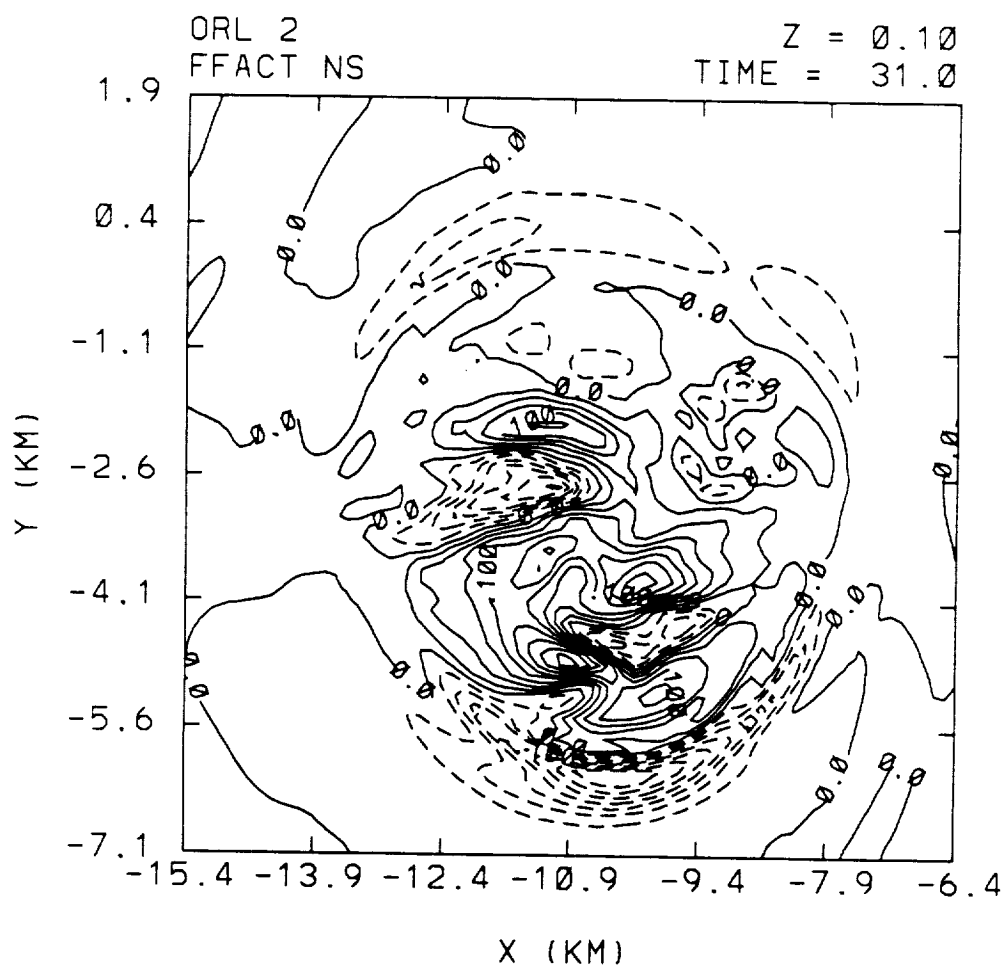
SIMULATED HORIZONTAL WIND VECTORS AT 30 M AGL



SIMULATED TEMPERATURE DEVIATION AT 100 M, CI = 1 ° C

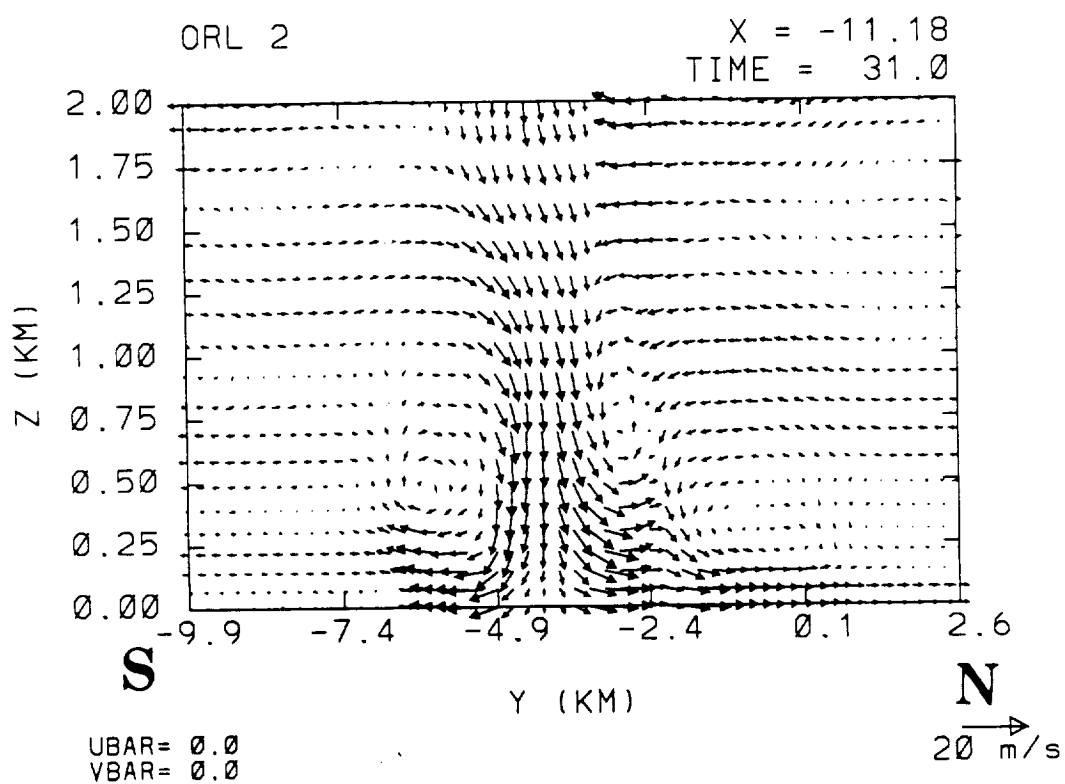


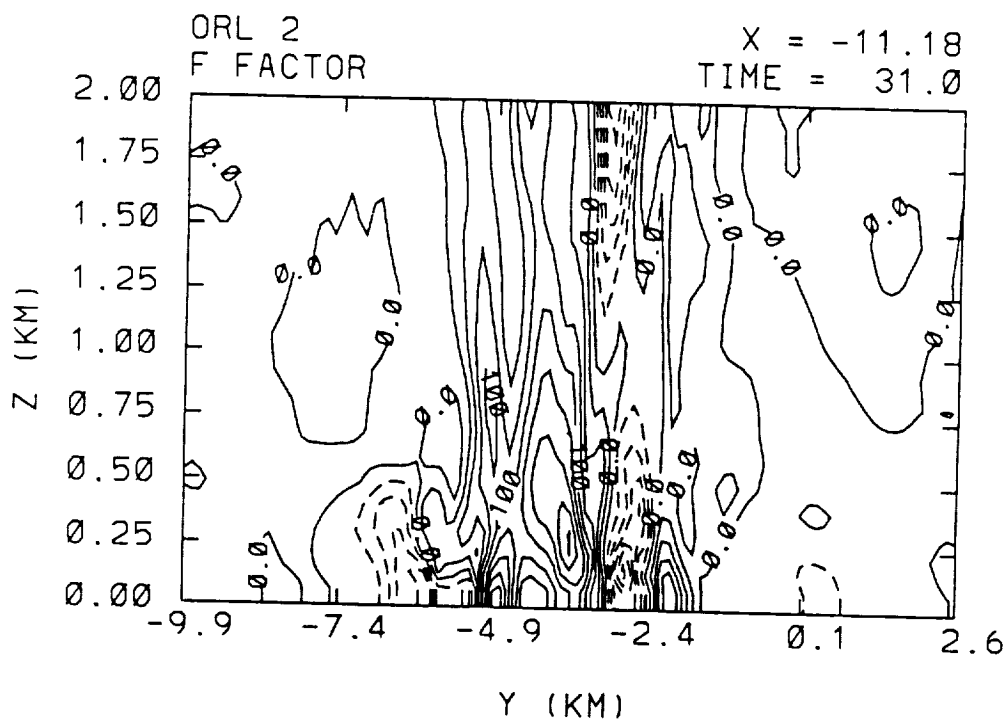
SIMULATED VERTICAL VELOCITY AT 220 M AGL CI = 1 M / S



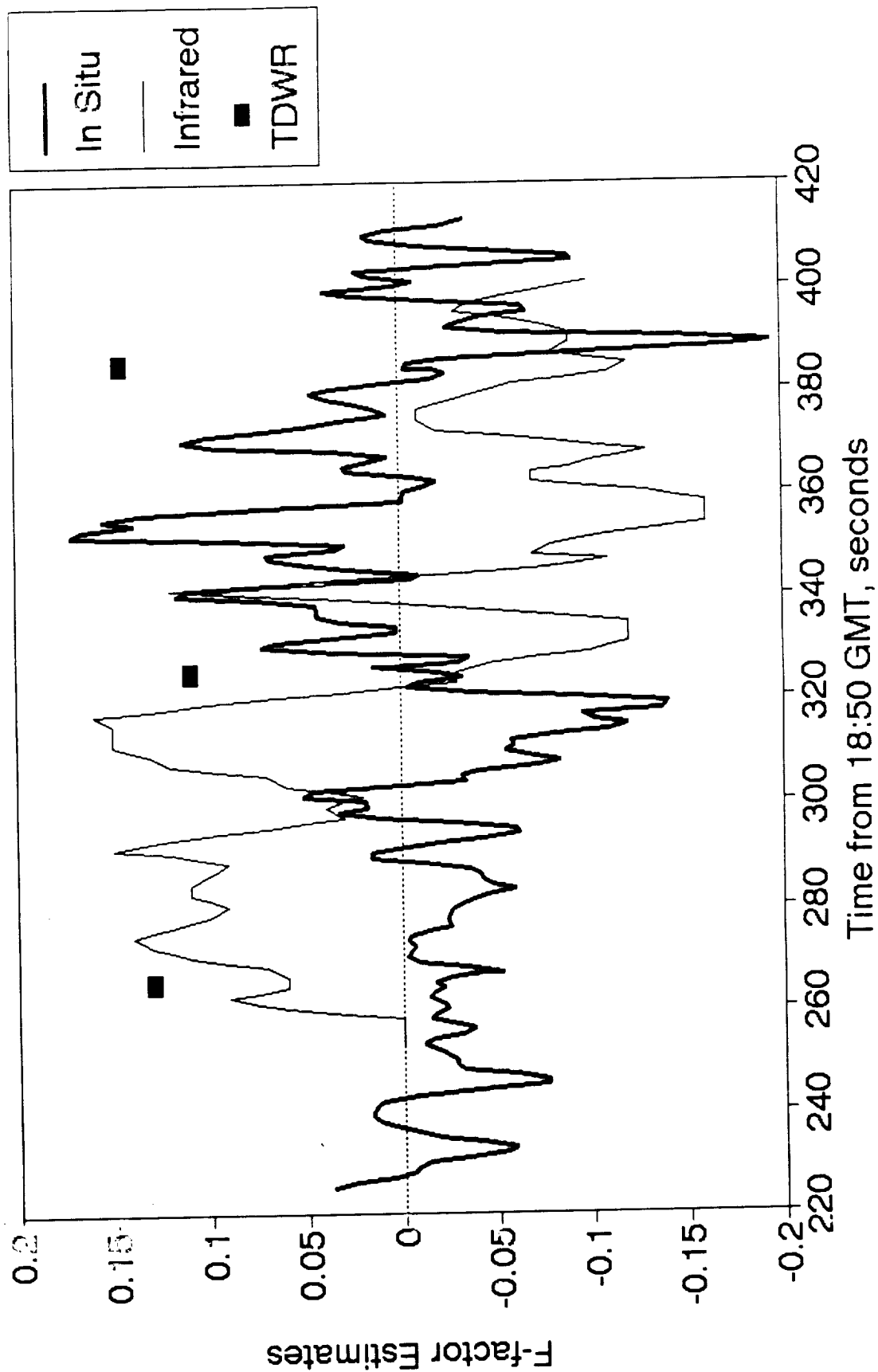
SIMULATED F-FACTOR AT 100 M AGL, CI=.025
(ASSUMES LEVEL FLIGHT PATHS ALONG NORTH SOUTH TRAJECTORIES)

SIMULATED NORTH - SOUTH CROSS SECTION WIND VECTORS





**NORTH-SOUTH VERTICAL CROSS SECTION OF
SIMULATED F-FACTOR, CI=.025**
(ASSUMES LEVEL FLIGHT PATHS ALONG NORTH SOUTH TRAJECTORIES)



**CITATION AIRCRAFT IN SITU F-FACTOR ANALYSIS
PENETRATION OF THE 7 JULY ORLANDO MICROBURST**

SUMMARY

- O WET MICROBURST WITH HAZARDOUS WIND SHEAR**
- O GOOD AGREEMENT BETWEEN SIMULATION AND OBSERVATION OF EVENT**
- O COMPLEX MICROBURST STRUCTURE:**
 - 1. MULTIPLE DOWNDRAFT CENTERS**
 - 2. AREAS OF UPWARD MOTION EMBEDDED WITHIN OUTFLOW**
 - 3. NON CLASSIC OUTFLOW AND F-FACTOR PROFILES**
- O PEAK ΔV OF 28.7 M/S ALONG EAST-WEST SEGMENT VS. 23.6 M/S ALONG NORTH-SOUTH SEGMENT**
- O TEMPERATURE DROP OF $\sim 6^\circ$ C AT TIME OF MICROBURST PEAK INTENSITY CONFORMS WITH PEAK ΔV OF 28.7 M/S; HOWEVER LARGER TEMPERATURE DROPS OCCUR NEAR THE GROUND DURING THE DISSIPATION STAGE**
- O PEAK VELOCITY CHANGE OCCURS ~ 8 MIN AFTER PRECIPITATION FIRST REACHES THE GROUND**
- O RAINFALL RATES EXCEED 5 IN/HR AND F-FACTORS EXCEED .15**

Model Comparison of July 7, 1990 Microburst - Questions and Answers

Q: CLEON BITER (NCAR) - Is there a reference that discusses the rule of thumb relationship that relates microburst velocity change to temperature drop?

A: FRED PROCTOR (MESO) - Yes. Journal of Atmospheric Science, Volume 46, 1989, Page 2143. This relationship is, the peak velocity change in meters per second is equal to the 5 times the value of the peak temperature drop in degrees C. Now, note that the peak velocity change and the temperature drop do not necessarily occupy the same place. In other words, the velocity change could be at a different elevation and position than the temperature. But anyway, we conducted a series of experiments with the asymmetric TASS simulation to examine this relationship and found that it worked very well in a number of cases. Although it certainly had several exceptions, those being when there were stable layers present, or if there were dry microbursts, or microbursts which originated as sublimating snow. This relationship doesn't tend to hold in decaying microbursts. In the case of decaying microbursts, you can still maintain some very cold temperatures near the ground, especially right along the surface where your getting evaporation of rain from the wet ground, yet the velocity changes begin to decrease.

Q: PETER ECCLES (MITRE Corp.) - Your model showed a temperature drop of about 10.2° C but your summary slide showed a temperature change of 6° C. Why is there a difference?

A: FRED PROCTOR (MESO) - The summary slide should read a 6° temperature drop during the peak intensity of the event and again, just for the reasons I mentioned before, the temperature at the surface in the simulation tended to decrease as the microburst decayed due to the evaporation of the wet ground. However, if you were to look up at a slightly higher elevation, you probably would not see much of a temperature drop.

Q: ED LOCKE (Thermo Electron Technologies): - Would you expect to see as good a correlation between the model and TDWR data for a dry microburst?

A: FRED PROCTOR (MESO) - Yes, in fact I'll be presenting results next week at the Severe Storms Conference in which we did a simulation of the Denver 11 July microburst, which was a borderline dry microburst, it had peak radar reflectivity of about 40 dBZ in the microburst. We seem to get very good velocity correlation with the TDWR.

Q: FRED REMER (University of North Dakota): - What is the forcing mechanism for the initiation of the July 7 microburst?

A: FRED PROCTOR (MESO) - I haven't evaluated the mechanisms for the forcing of this case, but looking at some of the data it certainly appears that loading is a significant factor. There was about 9 grams per cubic meter of rain water as the microburst came down. The mass loading from that amount of rain water would be equivalent to the same affect of a temperature drop of about 3 degrees. Certainly evaporative cooling would still play an important role as the down draft began to propagate below the cloud base level where the lapse rates were more or less adiabatic. Since there was little ice in this event I expect that the effects of melting and sublimation to be almost negligible. Certainly for other cases and events the mechanisms such as loading and sublimation would have various intensities.

Session III. Flight Management

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Session III. Flight Management

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Microburst Avoidance Simulation Tests
Dr. John Hansman, MIT

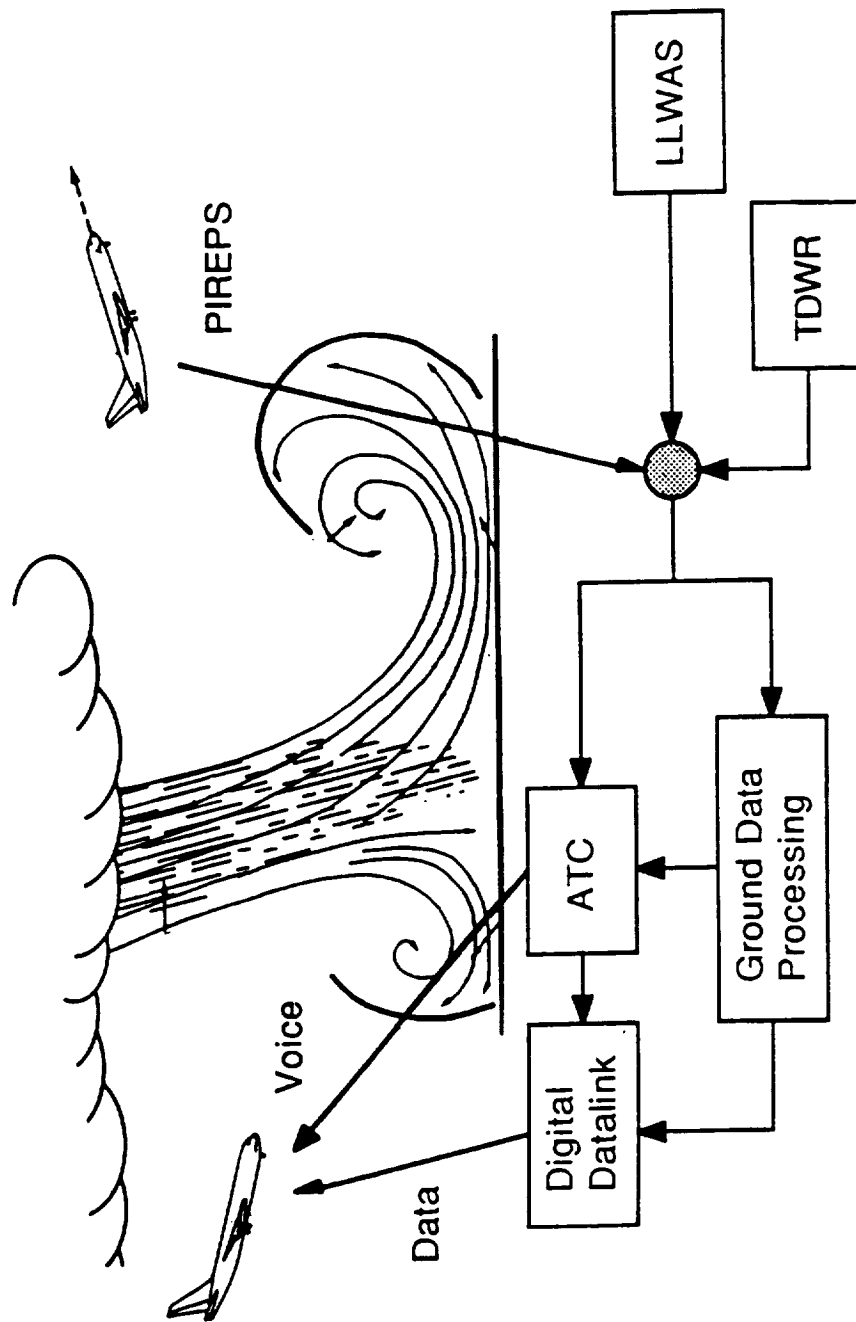
IMPLEMENTATION ISSUES FOR UPLINKED MICROBURST ALERTS

Dr. John Hansman and Craig Wanke
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge, MA

Third Combined Manufacturers' and Technologists'
Airborne Wind Shear Review Meeting
October 16-18, 1990 Hampton, VA



WINDSHEAR AVOIDANCE IN THE ADVANCED ATC ENVIRONMENT



RESEARCH FOCUS

- OVERALL: EVALUATION, TRANSMISSION, AND PRESENTATION OF GROUND-BASED DOPPLER WEATHER RADAR DERIVED INFORMATION THROUGH A LIMITED BANDWIDTH DIGITAL DATALINK.
- ELECTRONIC COCKPIT PRESENTATION OF UPLINKED WINDSHEAR ALERTS
 - PILOT OPINION SURVEYS
 - PART-TASK SIMULATION EXPERIMENT
 - PRESENTATION MODES:
 - VERBAL:* Standard radio communications
 - TEXTUAL:* Electronic presentation of the literal text of the message
 - GRAPHICAL:* Combined pictorial/text presentation of alert information on an electronic map-like display
- HAZARD EVALUATION OF GROUND-MEASURED WINDSHEAR DATA

PILOT OPINION SURVEYS

- Obtain flight crew evaluations of current windshear warning and avoidance systems and procedures
- Obtain flight crew feedback on future windshear warning systems and possible display formats
- Distribution: 250 United A/L flight crews
- Current Data Set: 51
51% of respondents have had a hazardous windshear encounter
- Data applications include design of part-task simulator experiments with advanced graphic and alphanumeric display formats and identification of data priority for datalink constraint analysis



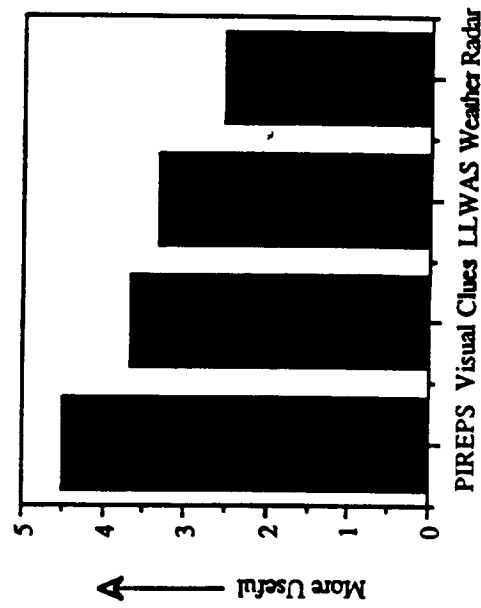
PILOT SURVEYS: GENERAL RESULTS

	<u>Agree</u>	<u>Disagree</u>
Microbursts pose a major safety hazard to transport category aircraft.	90.2%	4.9%
Currently available windshear alert data is sufficient for safe operation.	14.6%	43.9%
A system to provide crews better and more timely windshear information is <u>necessary</u> .	97.6%	0.0%
<ul style="list-style-type: none"> • Perceived windshear warning threshold: • Who should have the responsibility for judging the threat due to a particular windshear event from the (assumed reliable) available data? 	Advisory: 10.6 kts Warning: 15.1 kts PILOT: 83.0% CONTROLLER: 9.5%	

PILOT RANKINGS

Usefulness for windshear avoidance of:

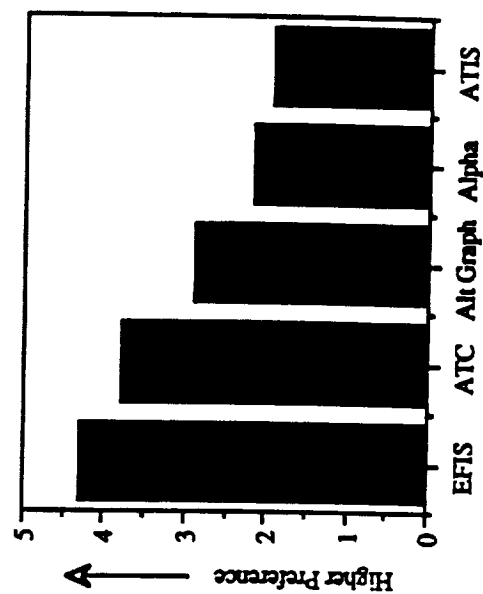
Pilot Reports
Visual Clues
LLWAS (Low Level Windshear Alert System)
Airborne Weather Radar



PILOT RANKINGS

Mode of data relay/presentation:

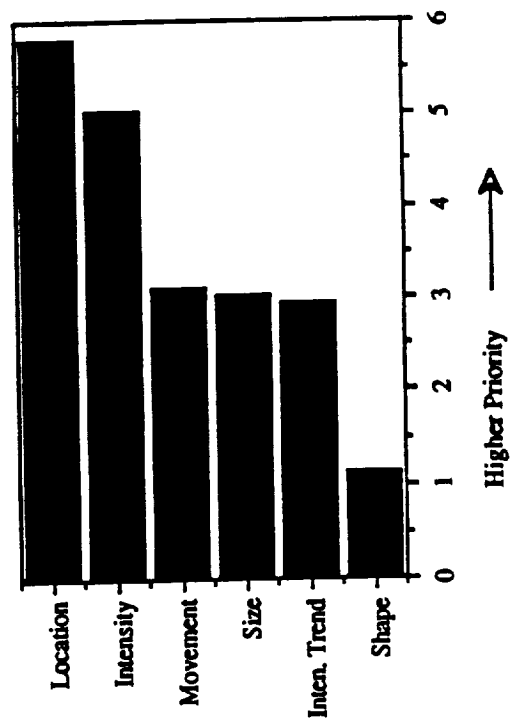
Verbal (ATC)
 EFIS EHSI (Moving Map) Display
 Alternate Graphical Display
 Alphanumeric Display
 On ATIS



PILOT RANKINGS

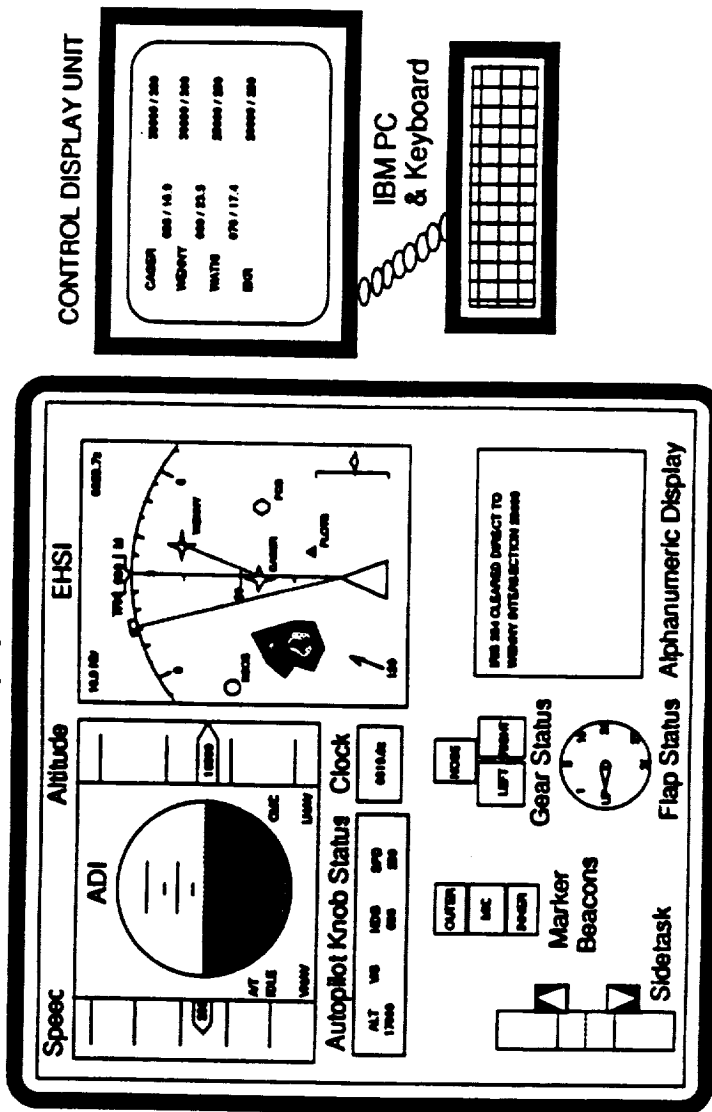
Usefulness of available windshear data:

Location	Size
Intensity	Intensity
Movement	Trend
	Shape



BOEING 767 PART-TASK SIMULATION

IRIS 2400T Display

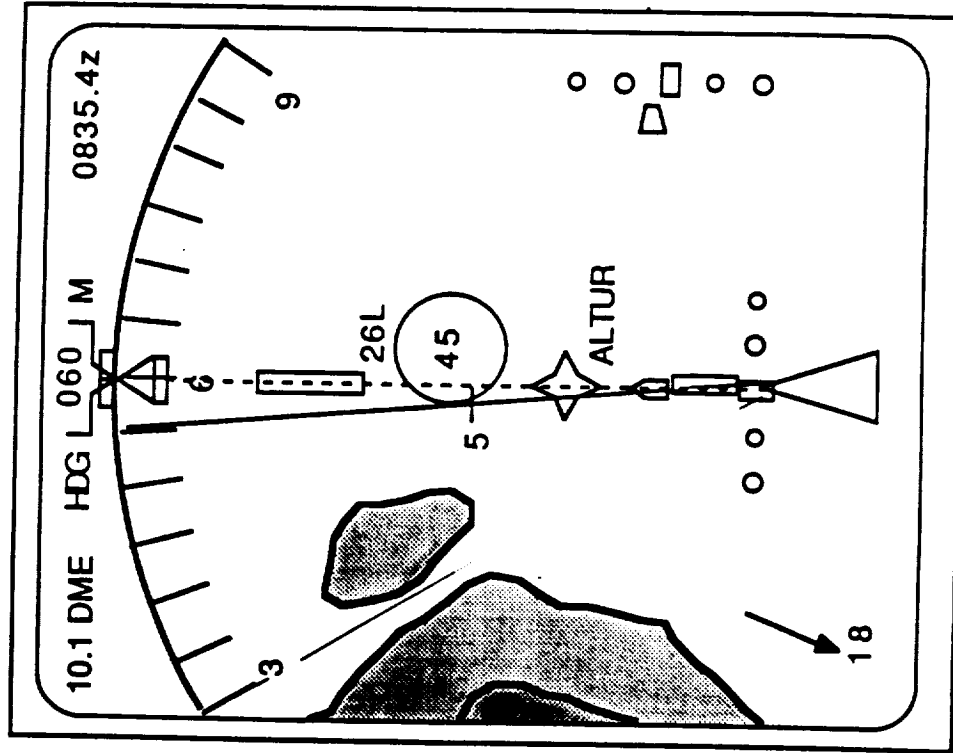
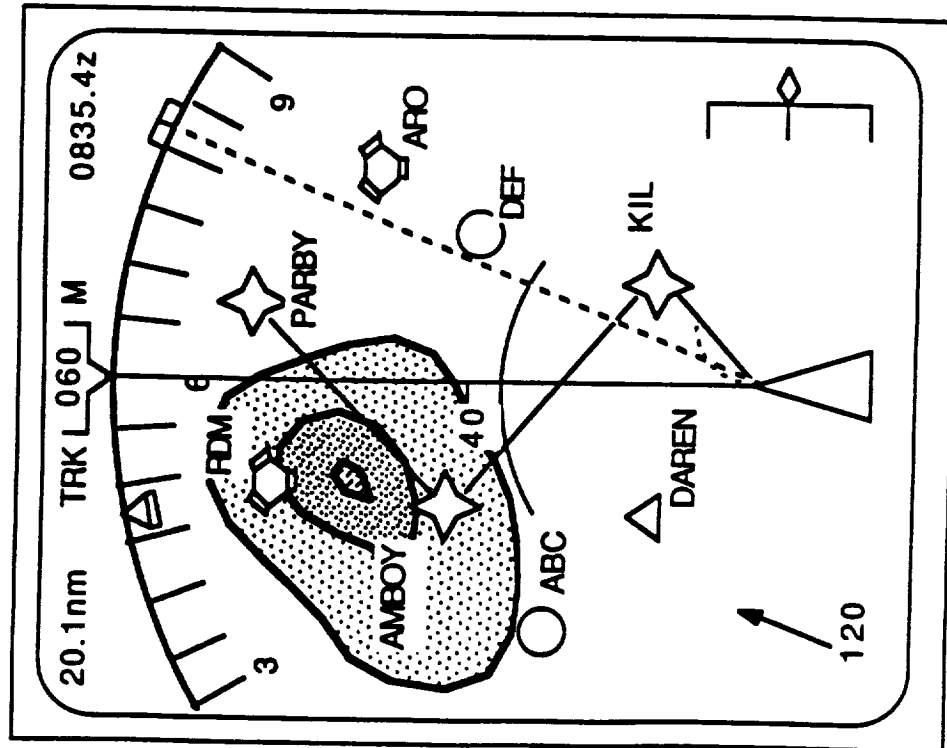


EHSI = Electronic Horizontal Situation Indicator
ADI = Attitude Direction Indicator

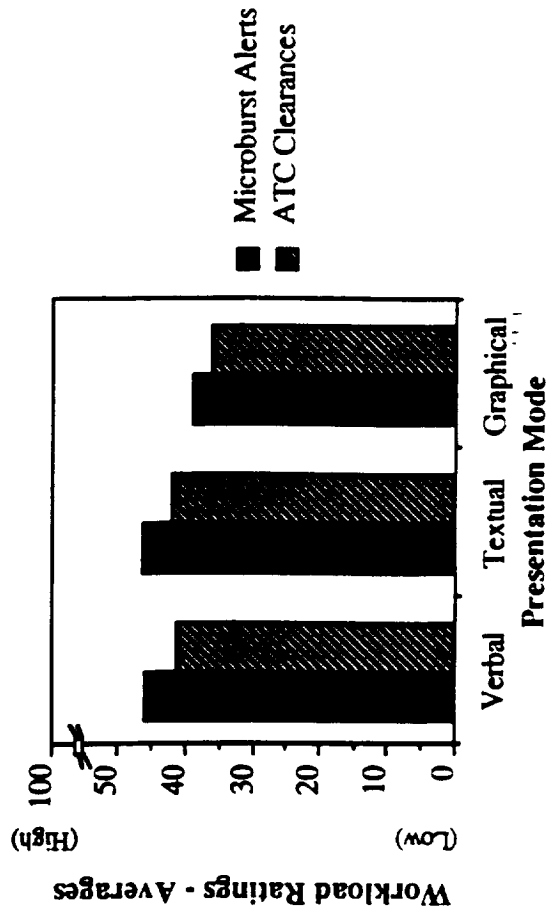
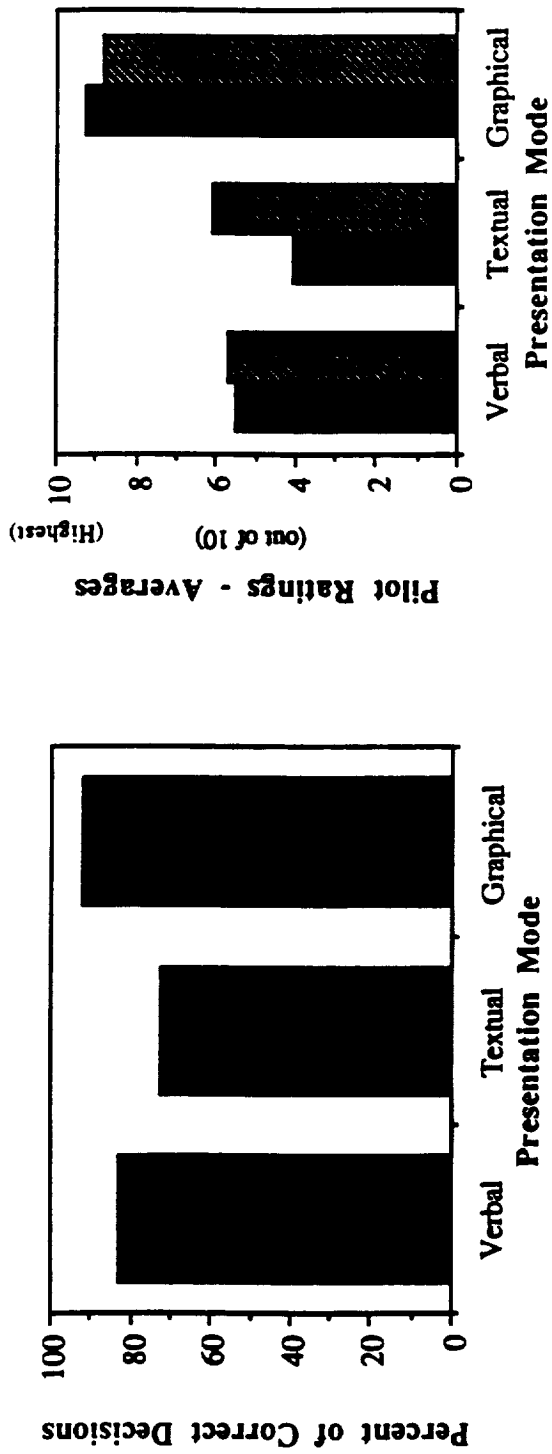
INITIAL EXPERIMENT

- Designed to compare verbal, textual, and graphical modes of windshear alert presentation
- Performed in concert with ATC clearance amendment delivery expt
- Subjects: 8 total, active 757/767 qualified line pilots
- 9 scenarios flown by each subject:
 - Descent and Approach to Denver-Stapleton Airport
 - 3 scenarios for each mode tested, groups rotated
 - Same information given in each mode, same mode used throughout each scenario
 - Descent: 3 ATC clearance amendments
 - Approach: microburst alerts - varying threat, alert time
- Sidetask, NASA subjective workload evaluation for workload monitoring
- Post-session debriefing

767 EHSI: MAP AND ILS MODES



SIMULATOR EXPERIMENT: MODE RESULTS



GENERAL OBSERVATIONS AND PILOT COMMENTS

- Positional info was more readily absorbed from graphical alerts
Missed approach planning
- Textual alerts in time-critical situations require too much head-down time, refocussing can be difficult for older pilots
- Loss of 'party line' and voice inflection information with digital datalink
- Lax attitude due to over-automation
- Graphical alert of microburst needs to be bright and easily interpreted, in contrast with original LLWAS implementation, for example
- Audible alert saturation problems
- Education about microburst encounter is necessary
- Positional information is great, but can the microburst threat be evaluated that exactly?

CONCLUSIONS: CREW INTERFACE RESEARCH

GRAPHICAL PRESENTATION OF INFORMATION IS DESIRABLE

- Pilot performance improved in both accuracy and speed
- Crew workload decreased
- Extremely positive pilot response to presentation
- Consistent with human cognitive mapping: speeds comprehension and improves situational awareness

TEXTUAL PRESENTATION IS NOT GENERALLY DESIRABLE

- No improvement over verbal communications in performance or workload reduction shown: subject to misinterpretation in time-critical situations
- Generally disliked by pilots
- Difficult to present clearly for quick scanning: added head-down time
- Elimination of copying errors
- Familiarity of aircrews with verbal communications

CONCLUSIONS: CREW INTERFACE RESEARCH

WINDSHEAR ALERT IMPLEMENTATION WITH DIGITAL DATALINK

- Minimum presentation: symbol with location, approximate size, intensity
- Mode-S datalink: 48 bits of info every 4 to 12 sec in surveillance mode
- TDWR update rate: 1 minute
- MODE-S LINK CAN BE USED TO DISPLAY AND TRACK SEVERAL MICROBURST EVENTS WITHIN TDWR UPDATE RATE

IMPORTANT ISSUES FOR USE OF DIGITAL DATALINK

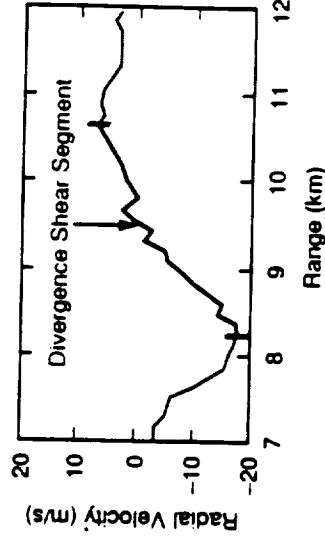
- Loss of 'party-line' communications
- Loss of prosodic (voice-inflection) information
- Additional head-down time required
- Information density considerations
- Over-automation problems: humans are poor monitors

HAZARD ASSESSMENT WORK: MOTIVATION

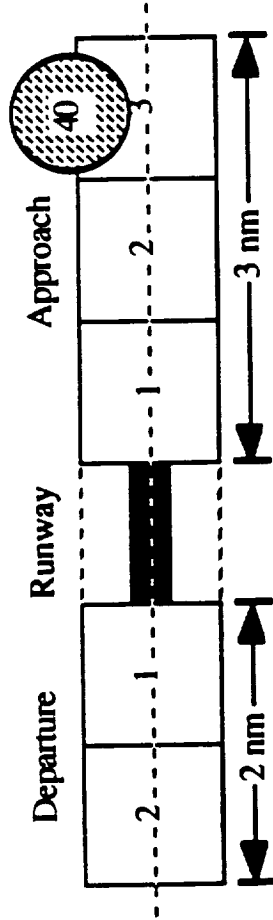
- TDWR OPERATIONAL EVALUATIONS
 - Overwarning is a problem - "Nuisance Alarms"
- PIREPS collected from 111 pilots who landed or took off during alert periods (Summer 1988 @ DEN):
 - 34% "Nothing was encountered"
 - 31% "Nothing much was encountered"
- Effect of overwarning:
 - Interference with normal airport operations
 - Reduced pilot confidence in alerting system
- Why does overwarning occur?

GROUND-BASED SINGLE DOPPLER MEASUREMENTS

- Reference frames: earth-fixed vs. aircraft fixed
Ground-based radar has area coverage
Airborne sensors know aircraft state, look along own flight path
- Terminal Doppler Weather Radar:
based off airport (~ 15 km) - does not look along runways
pencil-beam of 1° half-power beamwidth
scan strategy designed to provide microburst update every minute,
gustfront update every 5 minutes
- Microburst detected by identifying segments of radial velocity divergence
- Groups of segments are "boxed", subjected to tests for strength and size, and identified as microburst regions



TDWR MICROBURST ALERTS



The alert corresponding to the 40 knot microburst pictured might be: "United 226, Denver tower, threshold wind one six zero at six, expect a forty knot loss on three mile final."

Possible contributing factors to overwarning problem:

- Microburst asymmetry
- Divergence as the intensity measurement
- Lateral displacement of microburst w.r.t. flight track
- Altitude variations in windfield
- Dynamics of pilot/autopilot/aircraft system

MICROBURST ASYMMETRY

- Microburst asymmetry ratio: the ratio of total headwind change through the cross-section of greatest change to the total change in the direction of least change.
- In the Joint Airport Weather Studies (JAWS) Project, multiple doppler radar measurements of Colorado microbursts were taken:
 - Average asymmetry ratio of greater than 2
 - Extreme cases of greater than 5
- A study of Oklahoma downbursts indicated asymmetries up to 5.5
- A single doppler measurement of one radial microburst slice can be significantly different from the shear intensity along another slice.

HAZARD CRITERION: F-FACTOR

Aircraft Energy Height:

$$h_p = \frac{E}{W} = \frac{V^2}{2g} + h$$

Using aircraft equations of motion with "small" flight path angles:

$$\dot{h}_p = V\left(\frac{\dot{V}}{g}\right) + \dot{h} = V\left(\frac{T-D}{W}\right) - V\left[\frac{W_x}{g} - \frac{W_z}{V}\right] + V\left(\frac{\dot{V}}{g}\right)$$

For a constant airspeed trajectory:

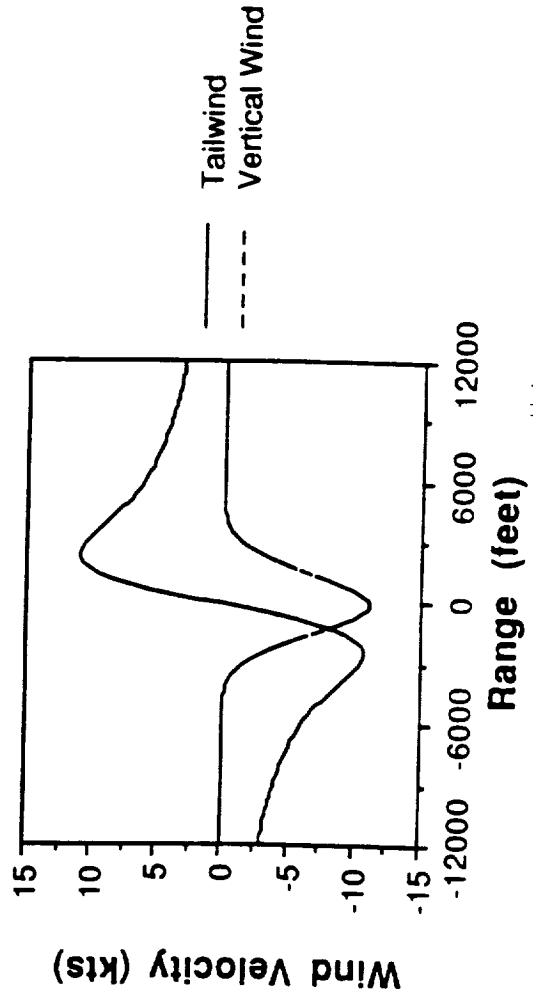
$$\dot{h}_p = V\left(\frac{T-D}{W} - F\right)$$

where F-factor is defined as:

$$F \equiv \frac{W_x}{g} - \frac{W_z}{V}$$

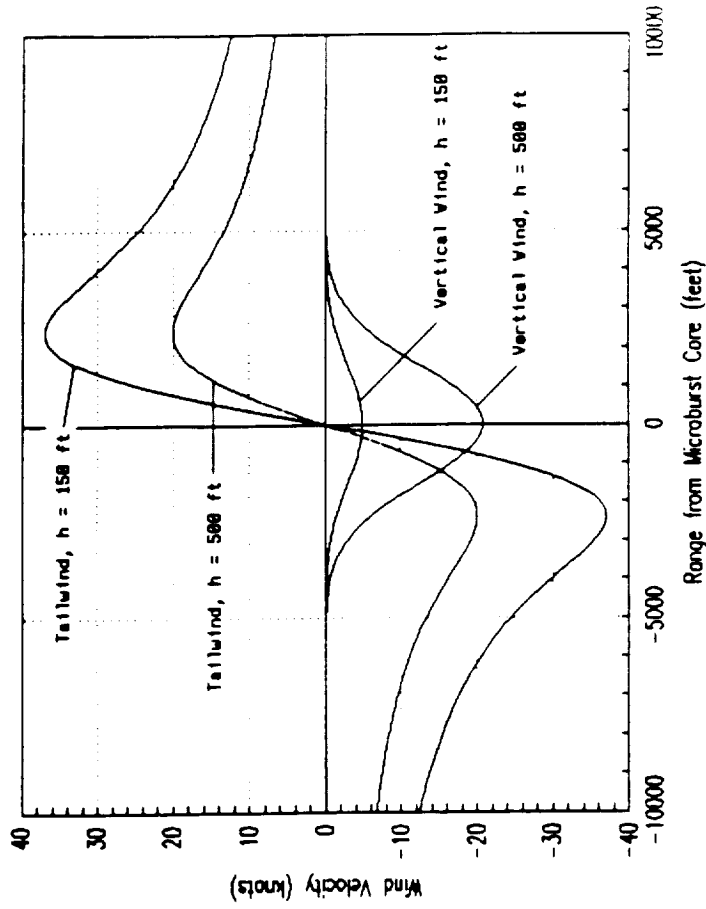
DIVERGENCE AS INTENSITY MEASUREMENT

- The maximum divergence measured is reported as "loss"
- Pilot interpretation: loss = maximum headwind change = maximum loss of airspeed when crossing center of microburst
- Actual airspeed change is function of control (energy management) strategy employed and F-factor, not explicitly divergence
- Airspeed loss vs. reference (commanded) airspeed as opposed to loss vs. maximum airspeed

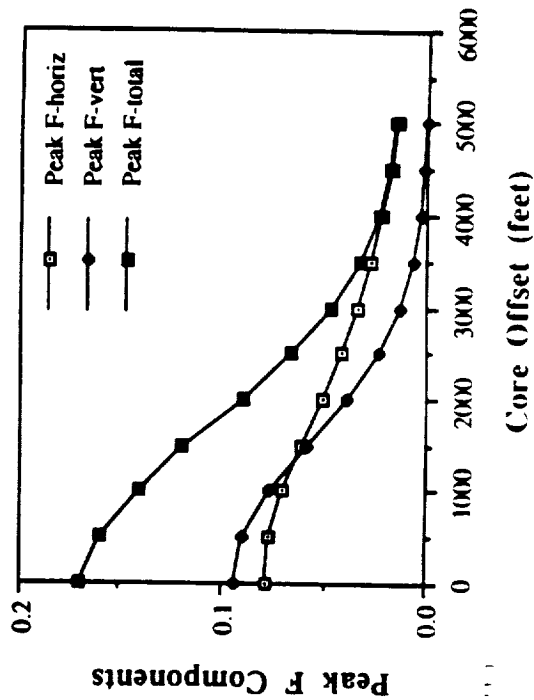
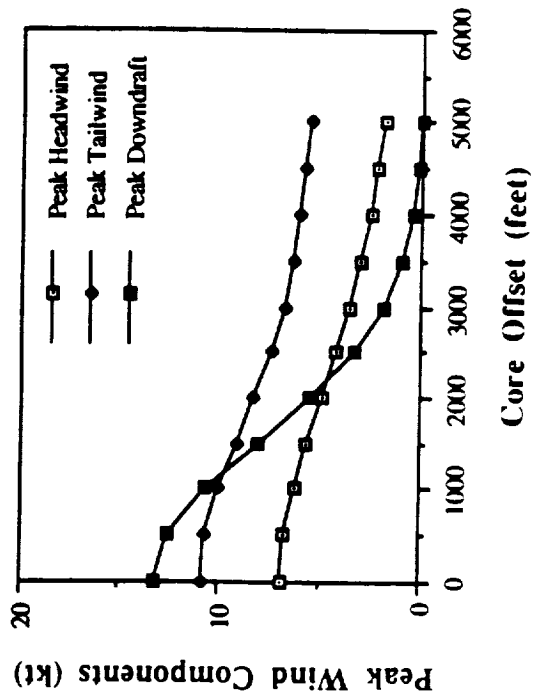
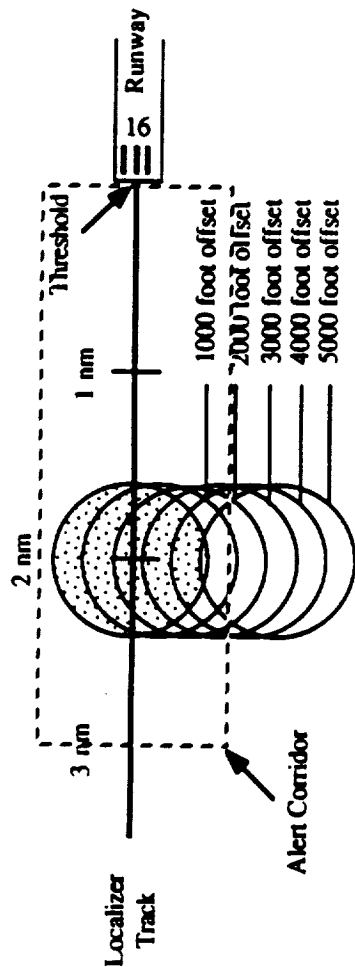


OSEGUERA AND BOWLES MICROBURST MODEL

- Based on boundary layer stagnation flow (wall jet) fluid dynamics, with relationships from TASS model
 - Axisymmetric, smooth 3-D windfield
 - Defined by 3 parameters:
 - Radius of downburst shaft
 - Maximum outflow velocity
 - Altitude of maximum outflow
 - Sample windfield at right:
 - Radius = 2133 feet
 - Max outflow = 37 knots
 - Altitude of max outflow = 120 ft
- "Footprint" is about 2400 feet

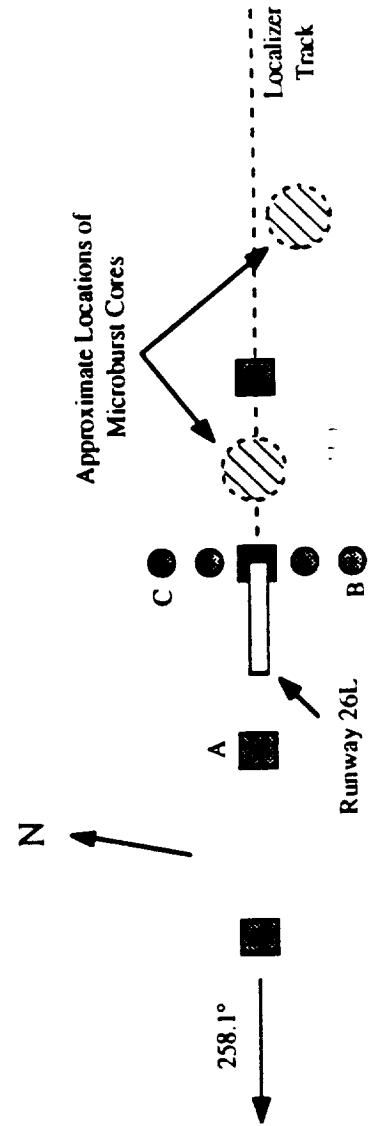
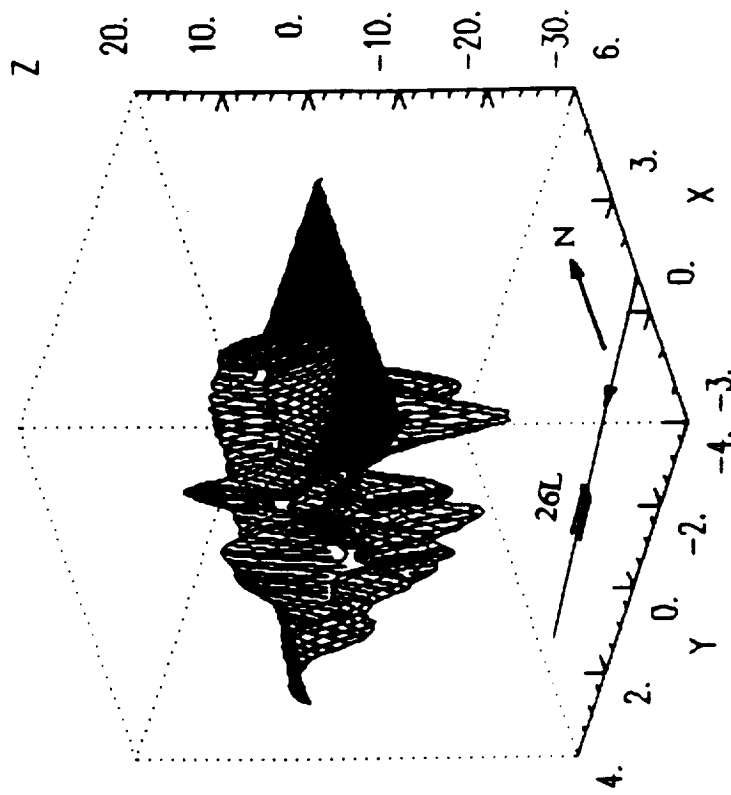


LATERAL DISPLACEMENT EFFECTS: O&B MODEL



TASS (Terminal Area Simulation System) MODEL

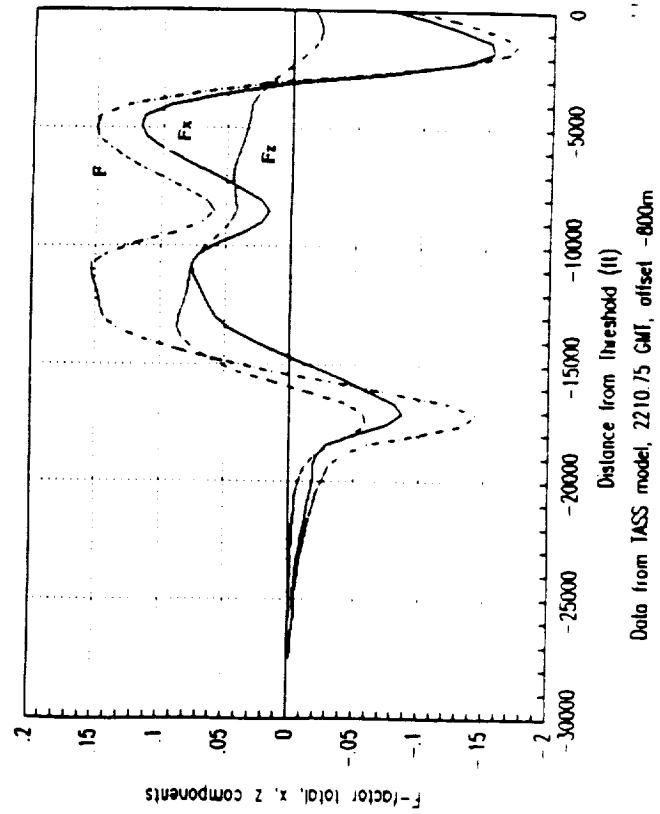
- Detailed numerical simulation of microburst dynamics
- Windfield computed for 7/11/88 event at Denver-Stapleton airport
- Full 3-D windfields for 5 times during event available for analysis



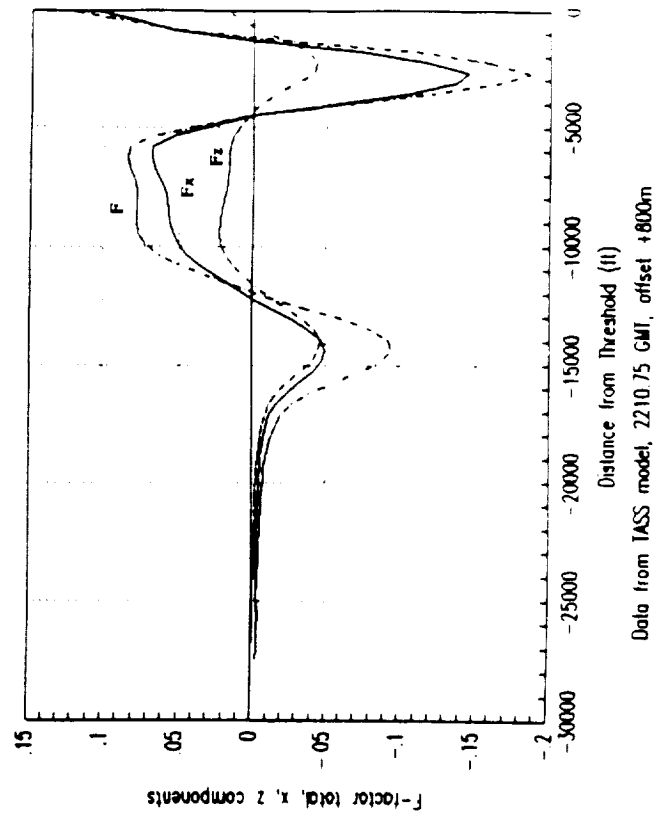
LATERAL DISPLACEMENT EFFECTS: TASS MODEL

- TASS windfields: Offset approaches to DEN 26L at 2210.75 UTC on 7/11/88. F-factor and its components are plotted.

Approach offset 0.5nm to South

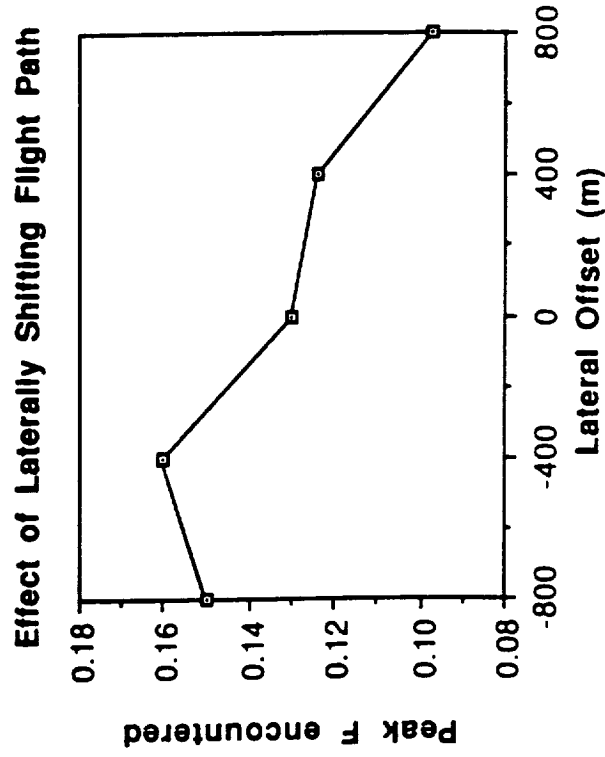


Approach offset 0.5nm to North



LATERAL DISPLACEMENT EFFECTS: TASS MODEL

- Windfields encountered during simulated approach to DEN 26L during 7/11/88 microburst event
- Runway displaced to North and South to demonstrate sensitivity of windfield to small lateral displacements



- Location of peak F along flight path also changes significantly

MICROBURST VARIATION WITH ALTITUDE

- Microburst windfields can vary strongly over the lowest 1000 feet AGL
- Hazard is due primarily to horizontal shear near the ground, primarily to downdraft at higher altitudes
- Finite radar beamwidth ($\sim 1^\circ$) causes weighted averaging of measured wind velocity over the lowest 500 to 1000 feet AGL
- Is the peak F-factor for paths through a microburst invariant with altitude?
 R. Oseguera model: YES
 TASS windfields: YES for fully developed single microbursts
 NO for developing microbursts, compound events
- Altitude invariance is useful if F is to be estimated from horizontal winds and microburst diameter only (as with TDWR measurement)

MICROBURST VARIATION WITH ALTITUDE

- O&B model microburst: 40 knot max divergence
Core encounter on approach at varying distance from threshold

Microburst Dist. From Threshold	Approx. Altitude of Encounter	Peak Winds (knots)			Peak F-factors		
		Headwind	Tailwind	Downdraft	F _x	F _z	F _{total}
1 nm	314 feet	12.1	18.7	8.21	0.13	0.058	0.19
2 nm	628 feet	6.82	10.8	13.2	0.078	0.094	0.17
3 nm	942 feet	3.85	6.10	16.1	0.044	0.12	0.16

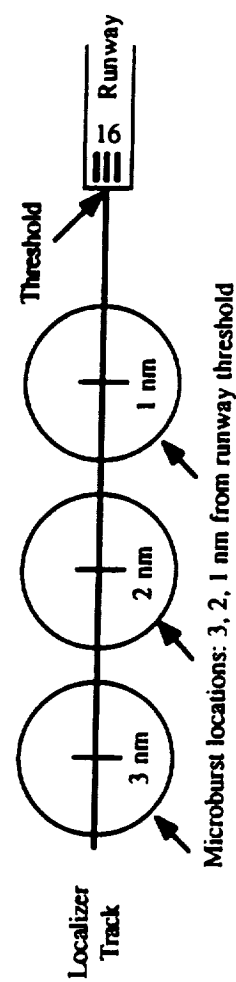
- TASS model windfield: July 11, 1988 simulation @ 2210.75 UTC
Core encounter on approach at varying distance from threshold

Runway Displacement	Approx. Altitude of Encounter	Peak Winds (knots)			Peak F-factors		
		Headwind	Tailwind	Downdraft	F _x	F _z	F _{total}
-1 nm	70 feet	26.1	14.7	3.50	0.083	0.025	0.11
0 nm	380 feet	21.6	24.2	7.32	0.090	0.052	0.13
+1 nm	690 feet	15.7	22.6	11.0	0.084	0.079	0.14
+2 nm	1000 feet	9.51	16.6	11.9	0.051	0.085	0.13

- How does the altitude-averaged divergence value measured by TDWR correlate to peak F?

FLIGHT PATH DEVIATIONS and F

- Deviations (airspeed and altitude) from the desired flight path are a function of the total F-factor profile and the energy management strategy used.
- Deviations are not dependent on whether or not the hazard is due to horizontal shear or downdraft.



Results from longitudinal Boeing 727 simulation through above windfields:

Microburst Dist. from Threshold	Max Deviations from Nominal Approach	Altitude Loss	Peak F-factors	F _x	F _z	F _{total}
1 nm (314 ft AGL)	13.7 kt	138 ft		0.13	0.075	0.19
2 nm (628 ft AGL)	12.6 kt	134 ft		0.094	0.092	0.18
3 nm (942 ft AGL)	11.6 kt	132 ft		0.071	0.10	0.17

IMPORTANT POINTS

- Overwarning during the TDWR Operational Evaluation due to lateral displacement of microbursts from aircraft track and difficulties in conveying hazard from divergence measurements.
- F-factor should be the hazard criterion, both from aircraft performance considerations and to allow fusion of data with airborne measurements.
- F-factor, although a natural measurement with airborne sensors, is difficult to estimate from the ground.
 - Contributing factors: no look along flight path, difficult to measure vertical winds, incomplete knowledge of aircraft state vector
- Since F is roughly invariant with altitude for models studied, should be able to couple TDWR measurements (horiz. wind, diameter) with fluid dynamic model to estimate F.

RECOMMENDATIONS

- Near-term TDWR alert modifications to reduce overwarning
Add: "left of approach," "right of approach," "on approach"
"divergence" vs. "loss"
- Improved pilot briefing about TDWR
- How to accurately estimate total F-factor from TDWR data?
Available data: measured velocities and reflectivity, features aloft,
known/correlated microburst characteristics, continuity,
analytical fluid-dynamic modeling
- Multi-level alert generation:
Alert levels correspond to recommended or required action by pilot
and/or controller
Alert thresholds defined for aircraft classes based on multiple data
sources: TDWR, LLWAS, PIREPS, Airborne sensors

CURRENT RESEARCH

- Development and evaluation of candidate crew procedures for use with multiple windshear sensors
 - airborne look-ahead sensors
 - airborne reactive sensors
 - ground-based sensors
- Further piloted simulations:
 - Evaluate graphical display formats and candidate crew procedures
- Improved microburst hazard assessment from TDWR data

Microburst Avoidance Simulation Tests - Questions and Answers

Q: SAM SHIRCK (Continental Airlines) - On graphic EHSI presentation can a pilot in a timely manner pull wind shear information from the EHSI when cluttered with weather radar returns, TCAS information, way points, etc., etc., etc. I like it, but can and will it work?

A: JOHN HANSMAN (MIT) - There is basically a problem of EHSI clutter, and as I said before, EHSI has become the most popular piece of real estate in the cockpit, everybody wants to put something there. I think it's a matter of good EHSI design. Currently you can deselect basically any piece of information off the EHSI, so you don't necessarily have to have the weather radar or the way points. You can deselect those. However, if you're going to put alert information up there you have to think about whether you're going to allow the crew to deselect alert information or not, probably not. And you would probably have to prioritize the alert information.

Q: PAUL KELLY (21st Century Technology) - Given the limitations on ATC voice communications, how sensible it is to depend on ATC voice for uplinking of hazard alert information like a TDWR microburst.

A: JOHN HANSMAN (MIT) - Clearly, if you have the equipment, the data link would be a more desirable system. It reduces the latency lag times inherent in ATC voice communication and gets rid of the frequency blocking effects. On the other hand, for the foreseeable future, and also in the third world, for example, you're probably not going to have data links and you're going to have to depend on voice for a long time.

Q: MARILYN WOLFSON (MIT Lincoln Laboratory) - You mentioned reduced wind shear hazard flying through the edge of the microburst versus going through the middle. Are there any significant known hazards from cross wind or leading vortex on the gust front?

A: JOHN HANSMAN (MIT) - We did do a study looking at cross wind effects and we actually found that if you penetrated the microburst just slightly off center, you got an increased performance loss due to cross wind and basically weather cocking effects and in fact that control gains required to keep the airplane on the straight trajectory on a slightly off center microburst were much higher. In fact, inordinately high which basically leads to the question, which we tend to ignore here, of the controllability in turbulence problem. F-factor is a good measure of the total integrated energy loss but if you look at some of the accident cases, Delta 191 is a classic example, that airplane hit the ground with a lot of energy. Some of the issues may be controllability issues which we tend to ignore because we basically don't have the measurements of the fine structure of the turbulence that's encountered. That's something to think about when we think about hazard criteria because it's a problem we wrestle with but nobody has a real clear measure of.

DAN VICROY (NASA Langley) - In regard to your controllability statement, we have done some work (about two years ago) where we tried to estimate not the performance impact but what the handling qualities impact of wind shear is. We did a simple analytical study that showed that when you're in that vortex roll, that can be a considerable handling qualities problem.

JOHN HANSMAN (MIT) - It should be pointed out that it's likely that the regions of high turbulence and handling problems probably correlate reasonably well with the areas of high F-factors. So, using F-factor as the criteria at the current status is probably not a bad idea.

UNKNOWN - If I could tell a personal story about running a 727 off the edge of the runway at Denver during the JAWS project. There was a case where unreported, just after touchdown, the airplane experienced enough of a cross wind from an associated suspected downburst that the airplane was blown completely off the dry runway. I've always contended that on take off and landing roll that the industry needs to take a look at some of the hazards rather than just figuring that the landing is complete after touch down.

JOHN HANSMAN (MIT) - That's an important point. Most of the analysis has been done for basically a two dimensional case, looking at the longitudinal dynamics. It's hard to do the analysis for the three dimensional lateral dynamics but there are cases where that can be very important. We didn't expect that when you displace the trajectory slightly, only about 100 or 200 feet off the center axis of the microburst, you actually get a significant increase in the performance degradation.

ROLAND BOWLES (NASA Langley) - To follow up on his point and what Dan said: with the question of cross wind and scales of turbulent motion on the order of the mean wing core and span of the airplane, you get into another problem. You've got to now address the question of how do you model the distributed aerodynamics of that airplane. You can have outboard sections on one wing stalling before another and that can be bad news. The lateral directional problem is very complicated. We found that conventional yaw dampers on big airplanes may actually, because of some root bifurcations going on in the dynamics, may actually hurt you rather than help you. You want to stay out of cross winds and scales of motion, severe ones anyway.

UNKNOWN - Most of the experiences we have with microburst penetrations are not actually symmetric penetrations, there's some degree of cross wind component. In fact, July 7 was a unique case because it was lined up on the runway on the center line it targeted. There was a strong cross wind in that case. Remember real world microbursts are not nice, perfect, axisymmetric events. Even when you're going through the center line or the mean center line of the event you can get and do get cross winds.

UNKNOWN - This has some interesting applications with regard to predictive sensors. With a 40 second warning, if the pilot makes the missed approach at 1000 feet, those problems are somewhat reduced. We're getting a lot of discussions in committees like the S7 about what to do if you have an alert with a predictive system. For example, AM539 following 191 got what would be a 28 second warning and went through the same event at about 3000 feet and 220 knots and didn't have much of a problem. So a lot of those problems go away if you've got some altitude when you go through the event. It bears on what predictive systems have to deal with and what people need to do when they get a predictive alert.

Session III. Flight Management

N 9 1 - 2 4 1 7 3

Wind Shear Training Applications for 91/135
Capt. Ed Arbon, Flight Safety Foundation

Operators

The requirement for windshear training of all pilots has been graphically demonstrated too often by the accident statistics of past years. While the tragic accidents such as New Orleans and Dallas receive most of the media attention, other aircraft operators have unfortunately experienced the same results when encountering windshear.

The need to expand the Windshear Training Aid that was developed by a team composed of The Boeing Company, McDonnell Douglas Corporation, Lockheed Corporation, United Airlines, Aviation Weather Associated, Hillwel, Inc working with FAA, NASA and other contributors to other segments of aviation was recognized immediately upon completion of the original project.

Slide #1

This group developed a classic document that has been used to train airline crews on the specific aircraft named in the Windshear Training Aid and to teach recognition of the meteorological conditions that are conducive to windshear and microburst formation.

Slide #2

The remaining aircraft operated in 1988, according to the FAA's General Aviation Activity and Avionics Survey, were over 200,000 aircraft in use by non FAR 121.0 scheduled airlines. These aircraft flew approximately 33,600,000 hours. It would be follow that some of this flying was exposed to the risk of a windshear or microburst encounter.

In order to verify that the example Windshear Training Aid information and guidelines are transferrable to other categories of aircraft. FAA, under the guidance of Cliff Hay and Herb Slickermaier, developed a project to test the concept. The Flight Safety Foundation, after concluding a teaming agreement with Flight Safety International, Simuflite and Flight Safety Services Corporation, responded to the RFP and was awarded a contract as the prime contractor.

Under the contract the group will test the transfer of the "Example Windshear Training Aid" on a sample test group of airplane pilots certified under 14 CFR Parts 91 and 135. This example is to include a representative cross section of both the domestic and international commuter, air taxi and corporate turbo-jet and turbo-prop aircraft flight simulators.

The program is to seek to demonstrate the effect of specific training on pilot performance. We are to demonstrate that during an inadvertent encounter with low altitude windshear that flight crew performance can be improved if pilots are trained in the techniques outlined in the "Windshear Training Aid". The principle lesson is avoidance. There are 120 crews in the test program who are divided into representative groups labeled A, B and C.

Training/testing is being done as follows:

A and B receive the entire WTA Group C only receive the ground school portion of WTA.

Group A are tested prior to and again after receiving the WTA.

Group B are tested after completing the WTA.

Group C is tested after the ground school portion of the WTA.

The crews in group "A" form a control group that receive no training prior to evaluation.

Group B receive specific training techniques in the simulator as detailed by the WTA for specific use in low-level windshear encounters prior to flying the test profile.

Group C receive only WTA ground school windshear avoidance and recovery training but no simulator training prior to flying the test profile.

Aircraft categories to be used are:

Turbo-prop

Twin-engine low thrust to weight turbo-jet

Twin-engine high thrust to weight turbo-jet

Three-engine turbo-jet

The aircraft chosen were

Saab 340

Cessna Citation III

Canadair 601

Falcon 50

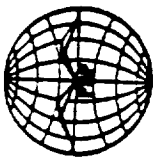
These aircraft were felt to represent a reasonable cross section of the contract requirements and simulators are available in addition to adequate supply of crews.

The project officially began on February 21, 1990 and the contract team is well into the testing phase. The data is being evaluated as it is accumulated. The first of four industry reviews will be held on October 25, 1990 at FAA headquarters at 800 Independence Ave. If any of you wish to attend and haven't received an invitation please see me.

It is anticipated that the WTA will prove to be a valuable to the 91/135 operators as it has been to those who use it as guidelines for their training today. I believe everyone here would agree that the WTA has made the industry understand and respect the windshear/microburst phenomena and has aided flight crews immeasurably.

As new technology is introduced this study will still be the backbone for recognition and avoidance of encounters.

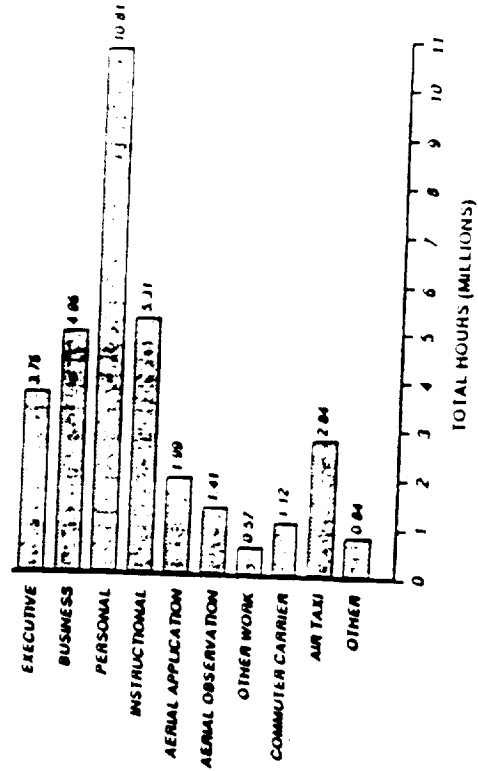
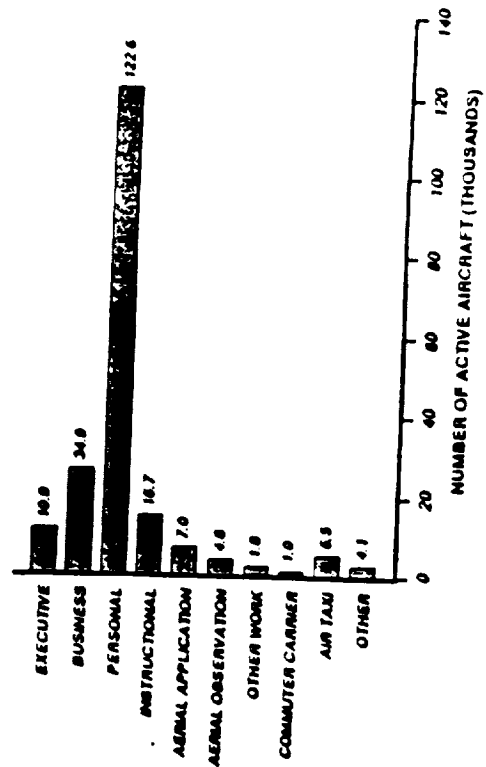
The product of our project, if we are able to prove the data is transferrable, will be our example WTA including the ground school course - Video and 35mm slides, 16mm film and a/c for Part 1/135 operations. This will be basically a re-issue of the original WTA.



Flight Safety Foundation



Figure 3.1
1988 GENERAL AVIATION NUMBER OF
AIRCRAFT AND TOTAL HOURS
BY PRIMARY USE



DISCLAIMER AND INDEMNITY NOTICE

This document, Windshear Overview For Management, and its companion documents, Pilot Windshear Guide, Example Windshear Training Program, Windshear Substantiating Data, and video presentations "A Windshear Avoided" and "Windshear What the Crew Can Do" were prepared pursuant to Federal Aviation Administration Prime Contract DFTA01-86-C-00005 with The Boeing Company as a training aid for flight in windshear conditions. The information contained herein and in the companion materials was derived from information originally developed for the Boeing 727, and provides a base-line training program with additional recommendations, developed and approved by Boeing, Douglas or Lockheed for their respective aircraft, regarding how that program might be adapted for use in specific commercial transport aircraft manufactured by Boeing [727, 737, 747, 757, and 767], Douglas [DC-9, MD-80, and DC-10] and Lockheed [L-1011]. ANY USE OF THIS WINDSHEAR OVERVIEW FOR MANAGEMENT FOR ANY PURPOSE RELATED TO AIRCRAFT OR CONDITIONS OTHER THAN THOSE SPECIFIED ABOVE IS NOT AUTHORIZED AND MAY RESULT IN IMPROPER AIRCRAFT OPERATION, LOSS OF AIRCRAFT CONTROL, INJURY AND LOSS OF AIRCRAFT AND LIFE. ANY USE, ADAPTATION AND/OR USE AFTER ADAPTATION OF THE MATERIAL IN THIS WINDSHEAR OVERVIEW FOR MANAGEMENT BY ANY ENTITY FOR ANY PURPOSE RELATED TO AIRCRAFT, CONDITIONS OR TO TRAINING PROGRAMS OTHER THAN THOSE SPECIFIED ABOVE SHALL BE COMPLETELY AT THE RISK OF THE ENTITY RESPONSIBLE FOR USING, ADAPTING AND/OR USING THE ADAPTATION OF THIS WINDSHEAR OVERVIEW FOR MANAGEMENT, AND SUCH ENTITY BY SUCH USE, ADAPTATION AND/OR USE AFTER ADAPTATION ASSUMES SUCH RISK AND WAIVES AND RELEASES ALL CLAIMS IT MAY HAVE AGAINST THE BOEING

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Notwithstanding any other provision of this contract to the contrary, the FAA shall accept the items delivered hereunder with the disclaimer affixed by Contractor and agrees not to remove such disclaimer for any reason whatsoever.

Wind Shear Training Applications for 91/135 - Questions and Answers

Q: WAYNE SAND (NCAR) - Even though we have not had a microburst accident involving air carriers for over 5 years, we continue to have numerous fatal accidents involving general aviation aircraft. General aviation includes aircraft less capable than the four being tested. Why isn't the training aid being adapted for these smaller general aviation airplanes?

A: HERB SCHLICKENMAIER (FAA) - What we're trying to put together is an application of the wind shear training aid for 91 and 135. 91 kind of covers everything. If there is some particular engineering issues that are unique to, and I'm not picking on one manufacturer over another, but are unique to a Cessna 150 that bear no resemblance whatsoever to operators of the Falcon 50 aircraft then, yes, I think there is an issue for some point of departure. Some of the hypothesis that the program office is putting together is that there's a body of knowledge that will transfer, in the model of flight crew action that starts all the way from wind shear weather evaluations through precaution and eventually to escape and recovery, if those conditions are met. And, that 91, whether its a 150 or a Falcon 50 may be able to make use of the wind shear weather evaluation portion regardless of the airplane type.

UNKNOWN - I think that the Cessna 150 has a lot less in common with the Falcon 50 than the Falcon 50 does with the 727. I mean we're talking about an airplane that has a very different wing loading, very different thrust to weight ratio, and a very different airspeed. Consequently, I think there is going to be less surprises with the executive jets in that study than there are for example for the Saab 340 and I think that what you learned from the Saab 340 may have more application for the Cessna 150 for example. It's not at all clear that the same procedures are going to apply for the single GA type aircraft. Whereas it's very possible that what you do for the Falcon 50 will look rather familiar.

ED ARBON (Flight Safety International) - The one thing I would like to point out is that we don't have the opportunity to use the advanced simulators for the other aircraft that we need to prove any of this hypothesis that we're talking about. So we have to use these categories. I hope you remember that we're using categories of airplanes that were chosen for certain specific things, low thrust weight, high thrust weight, three engine and the turbo prop, which are representative of the commuter industry. The other side of the coin is the fact that in the Cessna 150 and such, the most important part of the wind shear training aid is the avoidance section and the recognition of wind shear conditions. That part we certainly hope is transferrable as is. But really the point is simply avoid the wind shear.

Q: WAYNE SAND (NCAR) - The GA guys that are out there are still getting killed on a one to two at a time bases, and on a very regular bases. My question is, if your not going to say anything to the GA guys, why not? If you are, I'd like you to tell me you are.

A: HERB SCHLICKENMAIER (FAA) - What are the four products we're looking at? We're looking at an update to advisory circular 0050 "Wind Shear", which is the basic informational document to everybody. We're looking at a ground school training curricula for 135 operators. We're looking at developing a 135 simulator training for those 135 operators who wish to use it. And we're talking about putting together a part 91 home study course with computer aided instruction, with videos, pamphlets, and informational documents to get the message out on the hazards, the need to avoid, what to do to look for it, how to coalesce the information and how to make a decision about it. In that regard, yes, we've got a product, the homestudy course and it is designed directly for 91 operators, not just corporates but for everybody.

Q: WAYNE SAND (NCAR) - Based on experience working with the GA community of flyers of 182's and such, the question has come up, when is something coming out for me? When is the Wind Shear Training Aid going to be adapted so that it really applies to the class of airplane I fly?

A: HERB SCHLICKENMAIER (FAA) - December 21, 1991.

PETE SINCLAIR (Colorado State University) - I agree with Wayne, as a GA pilot and researcher, we use small aircraft and there's really no connection between your simulator approach which involves stick shaker and all those kinds of things to the GA airplane. We've flown many microbursts and the GA airplane on penetration has to do something quite different. You're not going to make the same penetration or have the same penetration procedure as you have in a Falcon or turbo prop for a GA airplane that has 500 to 700 feet per minute rate of climb capability. It just isn't the same. So you're going to have to write your manual quite differently and that's why we're still having these accidents. Wayne's perfectly right, we have these accidents over the mountains where there's no recovery altitude at all. The GA airplane is at maximum altitude and now it gets into a microburst from the clouds that are sitting right over the peaks and there is no capability at all to recover. We can't apply any of the techniques you're talking about here. I think that's an important question. A lot of GA accidents are classed as something else but they're really microburst operations.

HERB SCHLICKENMAIER (FAA) - I won't argue, Peter, with you or with Wayne. This is an issue we're taking a look at. Whether we will be able through the testing of Group C, the ground school instruction group, to determine whether there will be that last loop in the model of flight crew actions that sits down and says "hey guys, when you've made a decision, this is what the recommendation is." Can we transfer that? That's part of the testing that Ed and his people on the contract team are trying to come up with. Will we be able to transfer that part? I don't know. But I've got to kind of think that in the information on how you evaluate the weather and how you figure what's going on out there before you get into it, there's got to be something valuable. We think that if it can transfer we're going to move it into the general aviation community as fast and as hard as we can.

PETE SINCLAIR (Colorado State University) - I agree with the weather part, but the procedural part for the pilots has to be quite different, I would think.

AL MATTOX (Airline Pilots Association) - So far we keep talking about wind shear detection or wind shear this or that or the other and as an operator I get really confused. It seems to me like we seem to think we've invented wind shear. Wind shear has been here for a long time in various forms. I submit that the training aide has done a lot for the community. But, there are different operators that look at that document with varying levels of enthusiasm. To take that document alone and say that this is the solution to what I think most of us are talking about, which is a recovery from a microburst, is totally different than the other piece of the pie. Which is, there has to be an operation philosophy in the cockpit, there has to be crew coordination, there has to be understanding of basic cross wind limitations. When I make the approach and I've got 50 knots of wind with gusts to whatever, I don't make the distinction between that as a wind shear and a microburst. It all has to be put in the same context. I don't think it's fair to give, as good as it is, the training aid more credit than it deserves. You've got to have some other stuff to support it.

HERB SCHLICKENMAIER (FAA) - I can't disagree with that a bit. What we're trying to do is follow a philosophy we've had with this program from the beginning, which is to provide incremental steps. We think there is some tremendous benefit to be gained by getting some information out to the general aviation community and the air taxi commuter community as early as possible. There is more to be done and you're absolutely right. We've been with wind shear for a long time. What we've got to do is, step by step, as we learn, put it together. I think getting the information out to a tremendous side of the community is the first step.

Session III. Flight Management

Determining Target Pitch Angle
Herb Schlickenmaier, FAA

Generalized Method of Determining Target Pitch Angle for the Windshear Escape and Recovery Maneuver

H. W. Schlickemaier
Determining Target Pitch Angle

Systems Technology Division, ARP-200
Federal Aviation Administration

(October 1978)
(Final)

Objective

Organize a set of technical documents that describe a method for determining target pitch angle for a windshear escape and recovery maneuver.

Technique

Operators --

What is the recommended target pitch angle?

"... The recommended target pitch angle for your aircraft is 15° , unless the manufacturer of your aircraft recommends otherwise"

Approach

Manufacturers --

How can it be determined?

- Kupcis, et al, described an approach, used in the development of the FAA Windshear Training Aid (February 1987).
- Bray described an approach based on an observation of the target pitch angles that were reported by Boeing, Douglas and Lockheed, during their development of the FAA Windshear Training Aid, to wit, the initial target pitch angle can be estimated using the stall angle of attack (AOA) for the aircraft.

Strategy

Supporting Analysis --

Do fixed wing airplanes stand up to Bray's hypothesis?

- Dassault has provided their target pitch angles -- as have all of the manufacturers of aircraft that are used in the current 91/135 study -- and their target pitch angles have been independently "validated" in flight and in advanced simulators.
- Since AOA is not called out in the FAR's, a reproduction of the stall tests is simulated, the new variable added to the list is pitch. The estimated pitch at the appropriate V_{stall} becomes the target pitch angle.
- Flight dynamic research is also being conducted that will describe:
 - an analytical methodology to determine target pitch angle, and
 - an analysis of Bray's hypothesis using OTA.
- A description of the larger issues revolving around TPA, such as:
 - turbojet versus propeller,
 - straight wing versus swept, and
 - clean-wing versus high-lift leading edge devices.

Conclusion

The FAA Windshear Training Aid delivered to the FAA in February 1987 by the contract team headed by Boeing, is a robust document that describes a method for reducing the pilot's exposure to the risk of encountering hazardous windshear by ensuring that the flight crew is well-trained.

The training is centered around the model of flight crew actions:

- Avoid known windshear -- windshear weather evaluation
- Be prepared if you're not quite sure -- precautionary techniques
- If you encounter a windshear, execute a windshear escape and recovery technique -- *power and pitch*.

The analysis into a generalized method for determining target pitch angle is a small piece of an integrated approach for the flight crew to make use of to mitigate the windshear risk.

Determining Target Pitch Angle - Questions and Answers

Q: FRANK DREW (Lockheed Austin Division) - Why are we looking for a max performance pitch angle rather than an angle of attack? It would seem I can get into real bad trouble by flying to a canned pitch angle if I don't integrate my vertical vector and my micro air mass velocity vector. Am I missing something?

A: HERB SCHLICKENMAIER (FAA) - No. I don't think you are. The question comes up, how do we get the information out in a general set of techniques that can be applied to the community? If you take a look at what Don Bateman and his guys at Sundstrand are doing or Joe Youssefi and the people at Honeywell and the rest of the people around the world that are building boxes that are taking a look at some sophisticated processing, and certainly when you get into the guts of what NASA's second generation reactive device are going to be doing; there's some processing going on there that's going to be incredible. When you're talking about a pilot who's just realized that they're sitting in the middle of a microburst, now what's the recommended "Oh gosh, what do I do here?" We're not asking you to go to a max pitch angle, we're never advocating stick shaker to go to directly. We're trying to come up with something that's moderating in between that gives you just a little bit of reserve when you get back down to the bottom. I always recommend you take a look at the issues appendix in the documented, the substantiated data document. It kind of references where those decisions were made and that was one of the points that came up during the training.

CARL YOUNG (Eastern Airlines) - In your presentation you spoke of pitch and power, not perhaps in those words, but that was the essence of it and no one has touched upon power so far and I do not see it on the agenda. My comment is there was one national resource specialist from the FAA that was quizzing whether using max available power was a good idea. In interviewing crews that have been through three serious wind shear incidences, to a man, they all said, we don't think we would have made it without all available power. Based on full authority digital engine controls and electronic engine controls and other assets that limit power, do we really think as an industry that that's a good idea? And I would also like to comment that General Electric, to their great credit, is the only large engine manufacturer that I know of that published their statistics to max performance with engine deterioration and that was 1017 degrees based on a 945 degree max EGT, and this was done for 5- 1/4 minutes. That's a tremendous spread.

HERB SCHLICKENMAIER (FAA) - At one point I had heard there was some discussions going on, I wasn't quite sure whether it was the NRS propulsion people or whether it was one of the folks out at one of the aircraft certification offices in propulsion, but the question came up about multiple near simultaneous failures, i.e., you find yourself in a wind shear, you go to take all available power and run the engine all the way up. The question as I recall is: "what happens if we over temp an engine and now we flame one out?" There have been some discussions going on with the manufacturers of the engines, the airplanes, and with the certification people. Quite honestly I don't know what the resolution of that is. From what we've seen from the case studies in past, as Roland has been aptly quoted, there is no replacement for excess thrust to weight available to extricate yourself out of a wind shear. Again, I recommend you take a look at the issues section in the back of the training aide for the 121 applications on those 9 aircraft. There was some discussion that went on in the appendix regarding moving the engine throttles all the way up, and I'd be hard pressed to quote it right now.

Session III. Flight Management

Probabilistic Reasoning for Wind Shear Avoidance
Dr. Robert Stengel, Princeton University
Alex Stratton, Princeton University

Artificial Intelligence Advisory System for Wind Shear Avoidance

3rd Combined Manufacturers' and Technologists'
Airborne Wind Shear Review Meeting

October 16, 1990, Hampton Virginia

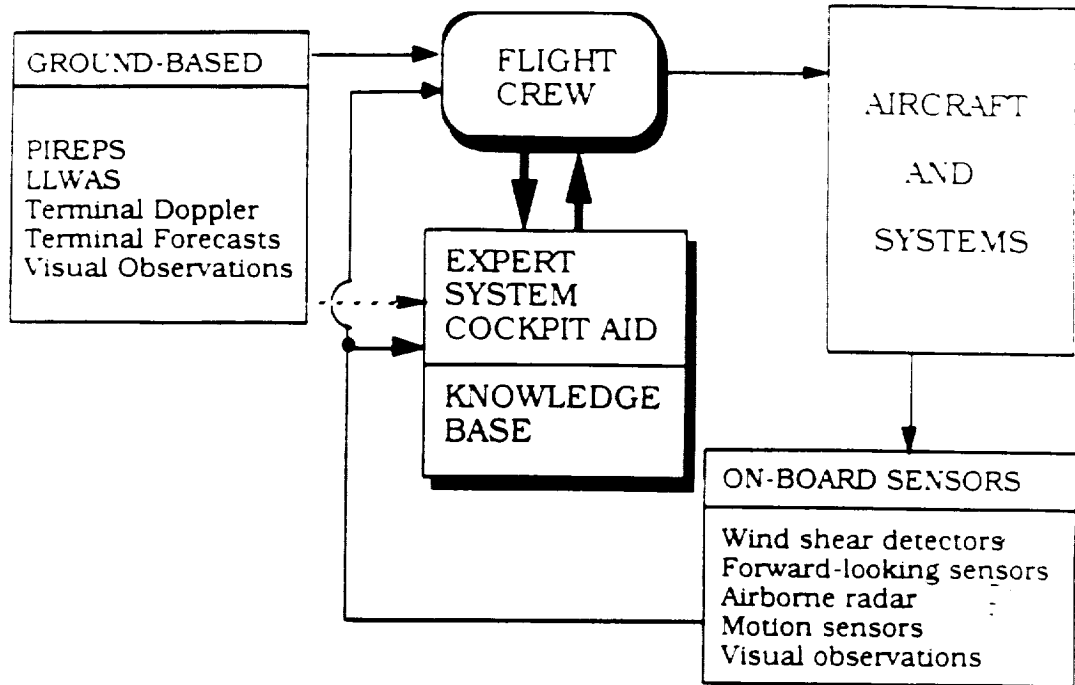
Presentation Outline

- An Expert System for Wind Shear Avoidance
- Risk Assessment and Probability Theory
- Probabilistic Model for Wind Shear Avoidance

Avoidance of Severe Wind Shear

- Remote wind shear detection
 - Airborne doppler radar, lidar, flir
 - Ground-based, TDWR, LLWAS
- Meteorological environment
 - NIMROD, JAWS, FLOWS
 - statistical results
- Flight crew training, guidance and control
 - F.A.A. Windshear Training Aid (1986)
 - Example training program
 - Precautionary, escape procedures
 - Avoidance guidelines

Expert System for Wind Shear Avoidance



- Increase crew decision reliability
 - Monitor sources
 - Prediction
 - Apply knowledge, assess risk
 - Recommend alternatives
- Rule-based implementation
 - ~200 "IF-THEN" rules
 - Goal-directed, cyclical search
 - Real-time, translation

Probability Theory for Risk Assessment

- Windshear Training Aid avoidance guidelines
 - "Low," "Medium," and "High" risk
 - Avoidance appropriate: "High" risk
 - "Low + Medium = High"
 - "Convective weather near flight path"
 - "Rainshowers" vs. "heavy precipitation"
 - "Use of [the avoidance guidelines] should not replace sound judgment."
- Probability theory
 - Widespread understanding
 - Meteorological statistics
 - Detection reliability statistics
 - Efficient implementation - Bayesian network

Elements of Probability Theory

- Condition probabilities: **Bayes's rule**

H: Hypotheses of wind shear

E1: Alert of wind shear

$$\Pr\{H \mid E1\} = \frac{\Pr\{E1 \mid H\}}{\Pr\{E1\}} \Pr\{H\}$$

Prior probability, $\Pr\{H\}$

Probability of detection, $\Pr\{E1 \mid H\}$

Probability of false alarm, $\Pr\{E1 \mid \neg H\}$

- Multiple evidence, structure

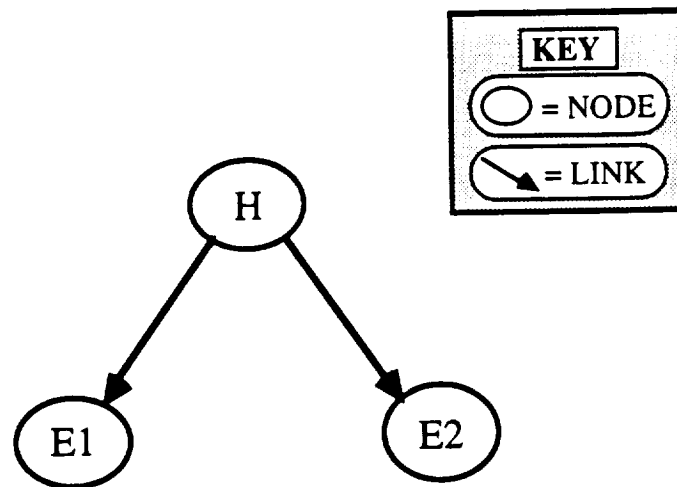
$$\Pr\{H \mid E1, E2\} = \frac{\Pr\{E1, E2 \mid H\}}{\Pr\{E1, E2\}} \Pr\{H\}$$

Conditional independence assumption:

alerts independent consequents of wind shear

$$\Pr\{H \mid E1, E2\} = \frac{\Pr\{E2 \mid H\}}{\Pr\{E2 \mid E1\}} \Pr\{H \mid E1\}$$

Graphical Representations of Dependency



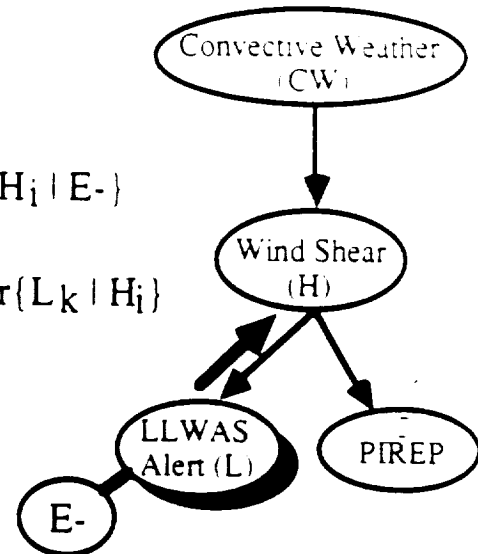
- Graphical representations
 - Hypotheses, Nodes
 - Dependencies, Links
 - Cause-effect, Arrows
- Causal hierarchies
 - Lightning, precipitation dependent
 - Independent given convective weather

Probabilistic Reasoning in Bayesian Networks

•Evidential Reasoning (Effect to Cause)

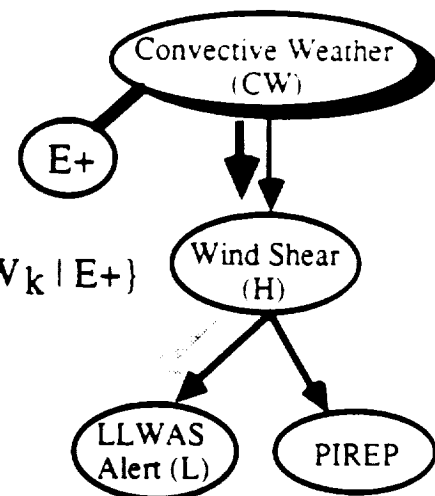
$$\Pr\{H_i | E-\} = \frac{\Pr\{E- | H_i\}}{\Pr\{E-\}} \Pr\{H_i | E-\}$$

$$\Pr\{E- | H_i\} = \sum_k \Pr\{E- | L_k\} \Pr\{L_k | H_i\}$$

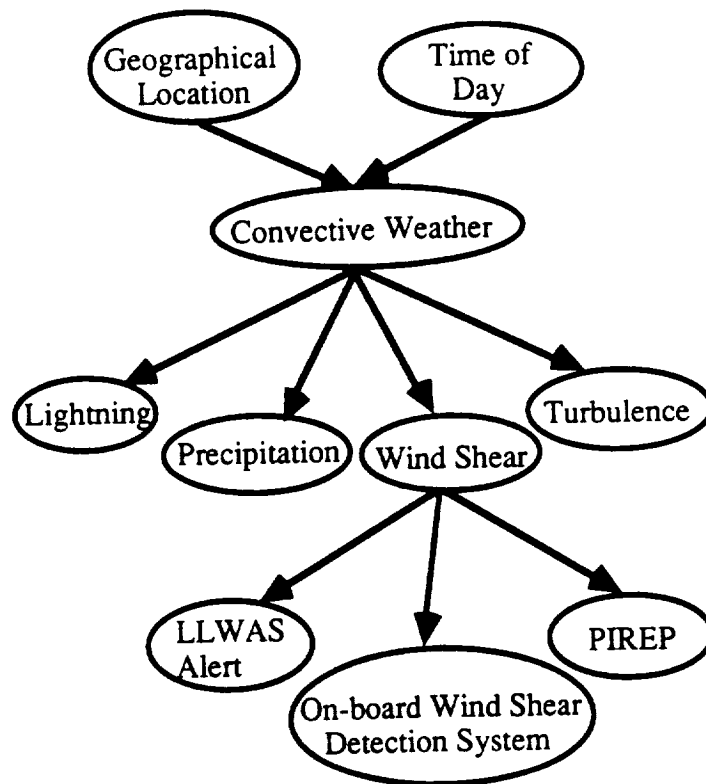


•Causal Reasoning (Cause to Effect)

$$\Pr\{H_i | E+\} = \sum_k \Pr\{H_i | CW_k\} \Pr\{CW_k | E+\}$$



Probabilistic Model of Windshear Training Aid Guidelines



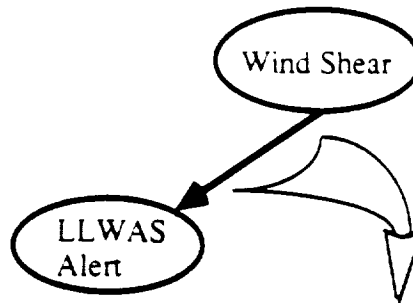
- JAWS, NIMROD, FLOWS, LLWAS
- Relevance to terminal operation
- Combined judgments involving uncertainty

Convective weather near flight path

Alerts versus weather features

"rainshowers" vs. "heavy precipitation"

Requirements for Probabilistic Representation



Given the level of wind shear on flight path is:	Severe	Moderate	Light
Probability of LLWAS Microburst Advisory is:	0.649	0.082	0.026
Probability of LLWAS Wind Shear Advisory is:	0.223	0.810	0.246
Probability of no LLWAS Advisory is:	0.128	0.108	0.728

- Link probabilities
Enhanced LLWAS, wind shear detectors
- Conditional weather and prior probabilities
JAWS, NIMROD, FLOWS
- Uncertain probabilities
Turbulence

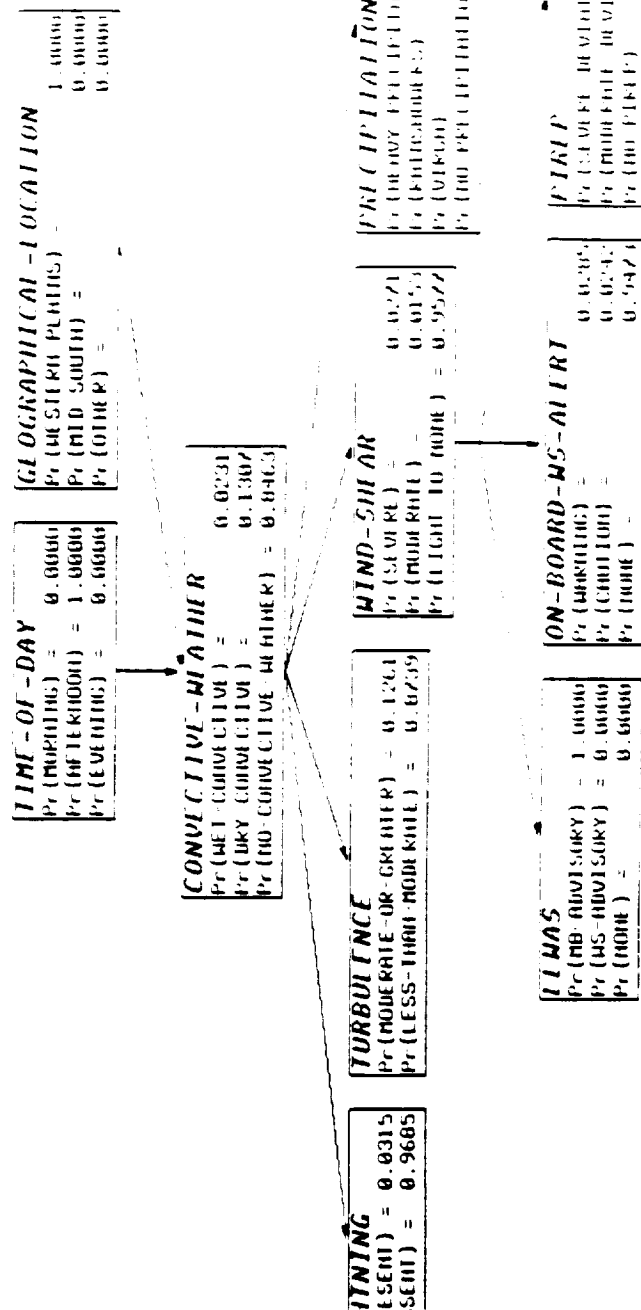
Demonstration of Probabilistic Reasoning

Bayesian Network Demonstration Utility

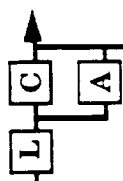
Beliefs	Clear	Display	Initialize	Load Definition	Make Node	New Definition	Submit
<div> <div> TIME-OF-DAY $Pr(\text{MORNING}) = 0.0000$ $Pr(\text{AFTERNOON}) = 1.0000$ $Pr(\text{EVENING}) = 0.0000$ </div> <div> GEOGRAPHICAL-LOCATION $Pr(\text{WESTERN-PLAINS}) = 1.0000$ $Pr(\text{MID-SOUTH}) = 0.0000$ $Pr(\text{OTHER}) = 0.0000$ </div> </div> <div> <div> CONVECTIVE-WEATHER $Pr(\text{WET-CONVECTIVE}) = 0.0180$ $Pr(\text{DRY-CONVECTIVE}) = 0.1040$ $Pr(\text{NO-CONVECTIVE-WEATHER}) = 0.8780$ </div> <div> PRECIPITATION $Pr(\text{HEAVY-PRECIPITATION}) = 0.0091$ $Pr(\text{RAINSHOWERS}) = 0.0192$ $Pr(\text{WIRGA}) = 0.0228$ $Pr(\text{NO-PRECIPITATION}) = 0.8997$ </div> </div> <div> <div> WIND-SHEAR $Pr(\text{SEVERE}) = 0.0011$ $Pr(\text{MODERATE}) = 0.0050$ $Pr(\text{LIGHT-TO-NONE}) = 0.9938$ </div> <div> PIREP $Pr(\text{SEVERE-DEVIATIONS}) = 0.0012$ $Pr(\text{MODERATE-DEVIATIONS}) = 0.0104$ $Pr(\text{NO-PIREP}) = 0.9684$ </div> </div> <div> <div> TURBULENCE $Pr(\text{MODERATE-OR-GREATER}) = 0.1103$ $Pr(\text{LESS-THAN-MODERATE}) = 0.8897$ </div> <div> ON-BOARD-WS-ALERT $Pr(\text{WARNING}) = 0.0024$ $Pr(\text{CAUTION}) = 0.0147$ $Pr(\text{NONE}) = 0.9830$ </div> </div> <div> <div> LIGHTNING $Pr(\text{PRESENT}) = 0.0258$ $Pr(\text{ABSENT}) = 0.9742$ </div> <div> ILWAS $Pr(\text{MB-ADVISORY}) = 0.0270$ $Pr(\text{WS-ADVISORY}) = 0.2468$ $Pr(\text{NONE}) = 0.7242$ </div> </div>							

Bayesian Network Demonstration Utility command: Load Definition "ISARC:\alex>belnet>def\initiations>risk2.lisp.newest"
 Loading ISARC:\alex>belnet>def\initiations>risk2.lisp.newest into package USER (really COMMON-LISP-USER)
 STARTING A NEW NETWORK DEFINITION.
 Bayesian Network Demonstration Utility command: Initialize Network (GEOPHICAL-LOCATION TIME-OF-DAY)
 Bayesian Network Demonstration Utility command: Display NETWORK (GEOPHICAL-LOCATION TIME-OF-DAY)
 Bayesian Network Demonstration Utility command:

Effect of LLWAS Microburst Advisory

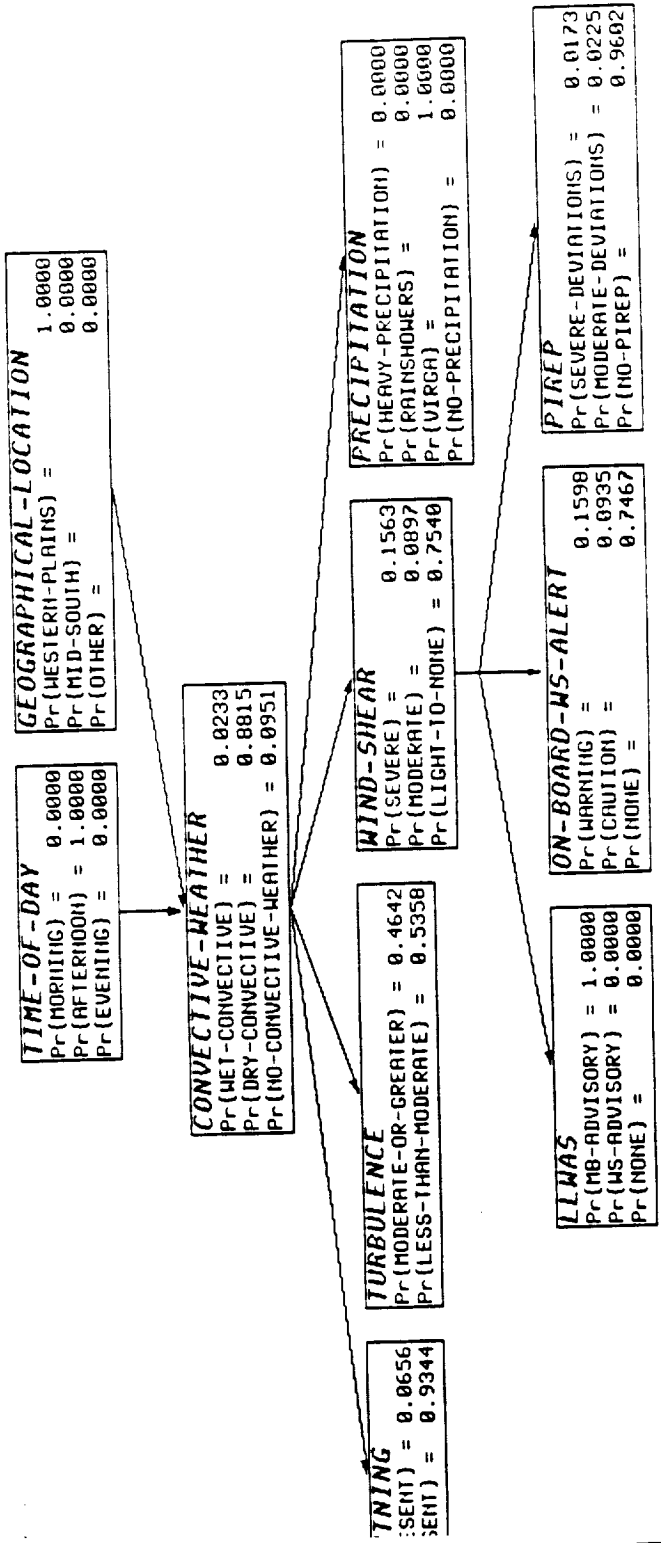


- PROBABILITY OF SEVERE WIND SHEAR INCREASES 2500 %



Laboratory for Control and Automation

Effect of Convective Weather Observation



• PROBABILITY OF WIND SHEAR INCREASES 600 %

Princeton University

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Conclusions

- Bayesian networks assimilate meteorological knowledge
 - manages uncertainty
 - fusion of evidence
 - stochastic prediction
- Probability provides scientific basis for avoidance guidelines
 - meaningful summaries
 - documented experience
- Uncertain probabilities
 - refinement by component
 - basis for meteorological studies

Session IV. Sensor Fusion & Flight Evaluation

Session IV. Sensor Fusion & Flight Evaluation

N91-24174

Integration of Weather Sensing Devices
Jim Daily, Honeywell Sperry

INTEGRATION OF WEATHER SENSING DEVICES

JIM DAILY
HONEYWELL, INC.

ABSTRACT

The state of airborne atmospheric sensing is continually evolving as devices are developed which further enhance the detection of meteorological phenomena. Assuming that these technologies prove to be feasible, the greatest long-term benefit would be attained by effective integration of the various sensors. A system which could accomplish this goal would conceivably provide enhanced atmospheric analysis, coherent display capability, and would allow for the development of expert systems to predict weather conditions.

This presentation briefly outlines the existing and developing weather detection technologies, followed by an overview of what issues must be dealt with in the creation of an integrated system. The presentation concludes with a framework of a basic system which identifies some of the potential applications that exist.

INTEGRATION OF WEATHER SENSING DEVICES

**JIM DAILY
HONEYWELL INCORPORATED
COMMERCIAL FLIGHT SYSTEMS GROUP
PHOENIX, ARIZONA**

INTRODUCTION **(WHY INTEGRATE?)**

AS ADDITIONAL DEVICES WHICH AID IN THE DETECTION OF ADVERSE ATMOSPHERIC PHENOMENA BECOME AVAILABLE, THE ISSUE OF HOW TO EFFECTIVELY INTEGRATE THE VARIOUS TECHNOLOGIES NEEDS TO BE ADDRESSED.

ALL THE VARIOUS TECHNOLOGIES HAVE POSITIVE CONTRIBUTIONS TO MAKE IN THE AREA OF HAZARDOUS WEATHER DETECTION AND AVOIDANCE. THE EFFECTIVE INTEGRATION OF THESE TECHNOLOGIES INTO A CONCISE SYSTEM WILL PROVIDE THE GREATEST LONG TERM BENEFIT.

OVERVIEW

- 0 INTENT IS MAINLY TO PRESENT ISSUES.
 - NOT ABSOLUTE SYSTEM DEFINITION.
- 0 FOCUS IS INTEGRATION OF DEVICES WHICH SENSE ATMOSPHERIC CONDITIONS.
 - PRESENTLY IMPLEMENTED AS WELL AS DEVELOPING TECHNOLOGIES.
- 0 ISSUES AFFECTING AN INTEGRATED SYSTEM.
 - DATA PROCESSING.
 - DATA PRESENTATION.
- 0 BASIC INTEGRATED METEOROLOGICAL SYSTEM.

BACKGROUND

- o ORIGINALLY, NO WEATHER SENSORS ON AIRCRAFT.
- THE NEED FOR ACCURATE WEATHER INFORMATION BECAME NECESSITATED DUE TO AIRCRAFT DAMAGE AND LOSS RESULTING FROM ATMOSPHERIC CONDITIONS.
- o PRESENTLY IMPLEMENTED AIRBORNE TECHNOLOGIES:
 - WEATHER RADAR
 - * RAINFALL LOCATION AND INTENSITY.
 - * TURBULENCE ASSOCIATED WITH RAINFALL.
 - * LIGHTNING (OPTIONAL).
 DISPLAYED ON WEATHER RADAR SCREEN.
 - PRECISE WIND MEASUREMENT AT AIRCRAFT
 - * REQUIRES PRECISE GROUND SPEED MEASUREMENT.
 - REACTIVE WINDSHEAR SYSTEMS
 - * ALERTS PILOT WHEN A WINDSHEAR IS EXPERIENCED.

BACKGROUND

o DEVELOPING AIRBORNE TECHNOLOGIES:

- DOPPLER RADAR
 - * LOOK-AHEAD WINDSHEAR DETECTION.
 - * REMOTE WIND MEASUREMENT.
- LIDAR
 - * LOOK-AHEAD WINDSHEAR DETECTION.
 - * REMOTE WIND MEASUREMENT.
 - * LOOK-AHEAD CAT DETECTION.
 - * WAKE TURBULENCE DETECTION.
- INFRARED/LOOK-AHEAD TEMPERATURE SENSING
 - * LOOK-AHEAD WINDSHEAR DETECTION.
 - * LOOK-AHEAD CAT DETECTION.

FORWARD LOOKING WEATHER DETECTION TECHNOLOGIES

	DOPPLER RADAR	LIDAR	PASSIVE INFRARED
WIND MEASUREMENT	RAINDROP TRACERS	AEROSOL TRACERS	THERMAL GRADIENT
TECHNOLOGY	<ul style="list-style-type: none"> NEW GENERATION WEATHER RADAR 	<ul style="list-style-type: none"> SOLID STATE AND GAS LASERS 	<ul style="list-style-type: none"> NEW GENERATION SENSORS
TECHNOLOGY READINESS	NEAR FUTURE	NEAR FUTURE	IN HAND
PERFORMANCE	<ul style="list-style-type: none"> GROUND BASED EXPERIENCE NASA FLIGHT TEST 	<ul style="list-style-type: none"> NASA FLIGHT TEST 	<ul style="list-style-type: none"> ACTUAL MICROBURST DETECTION
WET MICROBURST	GOOD	POOR	MARGINAL TO GOOD
DRY MICROBURST	POOR	GOOD	GOOD
ADVANTAGES	<ul style="list-style-type: none"> COULD COMPLEMENT WEATHER RADAR USING EXISTING RADOME, DISPLAY, ETC. 	<ul style="list-style-type: none"> CAT DETECTION ENROUTE WINDS WAKE TURBULENCE 	<ul style="list-style-type: none"> LEAST COMPLEX INEXPENSIVE CAT DETECTION PASSIVE SYSTEM
MAJOR TECHNICAL PROBLEMS/RISKS	<ul style="list-style-type: none"> REMOVING GROUND CLUTTER DRY MICROBURST TILT MANAGEMENT VERT. WIND MEASUREMENT 	<ul style="list-style-type: none"> HARDWARE COMPLEXITY/COST MAINTENANCE LASER LIFE OPERATION IN HEAVY RAIN VERT. WIND MEASUREMENT WEIGHT POWER REQUIREMENTS 	<ul style="list-style-type: none"> INFERENCE NUISANCE DET. HORIZ. WIND MEASUREMENT DEGRADATION IN RAIN MAINTENANCE

TECHNOLOGY SUMMARY

THE EXISTING STATE OF ON-BOARD DETECTION OF ADVERSE ATMOSPHERIC PHENOMENA COULD BE SIGNIFICANTLY ENHANCED BY THE INCLUSION OF SOME OR ALL OF THE DEVELOPING TECHNOLOGIES.

- NONE OF THE THREE FORWARD LOOKING TECHNOLOGIES HAS YET BEEN PROVEN TO BE A UNIVERSAL SOLUTION FOR DETECTION OF ADVERSE WEATHER.
- WHERE ONE TECHNOLOGY MAY SUFFER, ANOTHER MAY EXCEL.
- THE IDEAL METEOROLOGICAL SYSTEM WILL CONTAIN MORE THAN ONE OF THESE TECHNOLOGIES COMPLEMENTING ONE ANOTHER.

DEVELOPMENT ISSUES

IN ORDER TO DEVELOP A SYSTEM WHICH INCORPORATES INPUTS FROM THE VARIOUS WEATHER SENSING DEVICES, THE FOLLOWING ISSUES MUST BE ADDRESSED:

- O HOW IS DATA ASSIMILATED FROM THE MULTIPLE SENSORS?**
- O HOW IS DATA PRESENTED TO THE PILOT IN A CONCISE MANNER?**
- O WHAT OTHER POTENTIAL APPLICATIONS MAY EXIST?**

DEVELOPMENT ISSUES

HOW IS DATA ASSIMILATED FROM THE MULTIPLE SENSORS?

O DISTRIBUTED SYSTEM.

- EACH SENSOR WITH COMPUTATIONAL CAPABILITY.
- RELEVANT DATA TRANSMITTED TO OTHER DEVICES.
- DISPLAY OPTIONS:
 - * INDIVIDUAL DISPLAYS FOR EACH SENSOR.
 - * CENTRAL DISPLAY UNIT PROCESSING OUTPUTS FROM THE SENSORS.

O INTEGRATED SYSTEM.

- CENTRALIZED PROCESSING OF SENSOR INPUTS.
- SENSORS ACT IN COMPLEMENTARY FASHION TO ONE ANOTHER.
- ENHANCED ATMOSPHERIC ANALYSIS.
- SINGLE, MULTI-FUNCTION DISPLAY.
- CAPABILITY FOR FORECASTING (EXPERT SYSTEM).

DEVELOPMENT ISSUES

HOW IS DATA PRESENTED TO THE PILOT IN A CONCISE MANNER?

o PRESENT DATA FOR PILOT EVALUATION.

- E.G. WEATHER RADAR.

o NOTIFY PILOT OF SIGNIFICANT EVENTS.

- E.G. WINDSHEAR ALERT.

o PROVIDE FORECAST OF ADVERSE WEATHER RISK FOR PILOT EVALUATION.

- "METEOROLOGIST IN THE COCKPIT" (EXPERT SYSTEM).

o COMBINATION SYSTEM.

- INTEGRATED METEOROLOGICAL SYSTEM BASED ON COMBINATION OF THE ABOVE DATA PRESENTATION FORMATS.

DEVELOPMENT ISSUES

ANY OTHER POTENTIAL APPLICATIONS?

O REPORTING DATA TO GROUND STATIONS FOR USE BY OTHER AIRCRAFT.

- METHOD FOR COMMUNICATING THE DATA REQUIRED.
- SYSTEMS TO ACCUMULATE/REDUCE THE DATA.

O OTHER WEATHER PHENOMENA THAT PILOT WOULD LIKE TO KNOW IN REAL TIME?

- ICING CONDITIONS.
- RAIN RATE AT THE AIRCRAFT - AOA/STALL EFFECTS.
- CHANGING WEATHER PATTERNS.

O INTERFACING WEATHER DATA TO OTHER AIRCRAFT SYSTEMS.

- ALTER FLIGHT PLAN BASED ON IMPENDING WEATHER CONDITIONS.
- GUIDANCE TO ESCAPE ADVERSE SITUATIONS.
- AUTOMATIC ACTIVATION OF DE-ICING SYSTEMS.
- ETC..

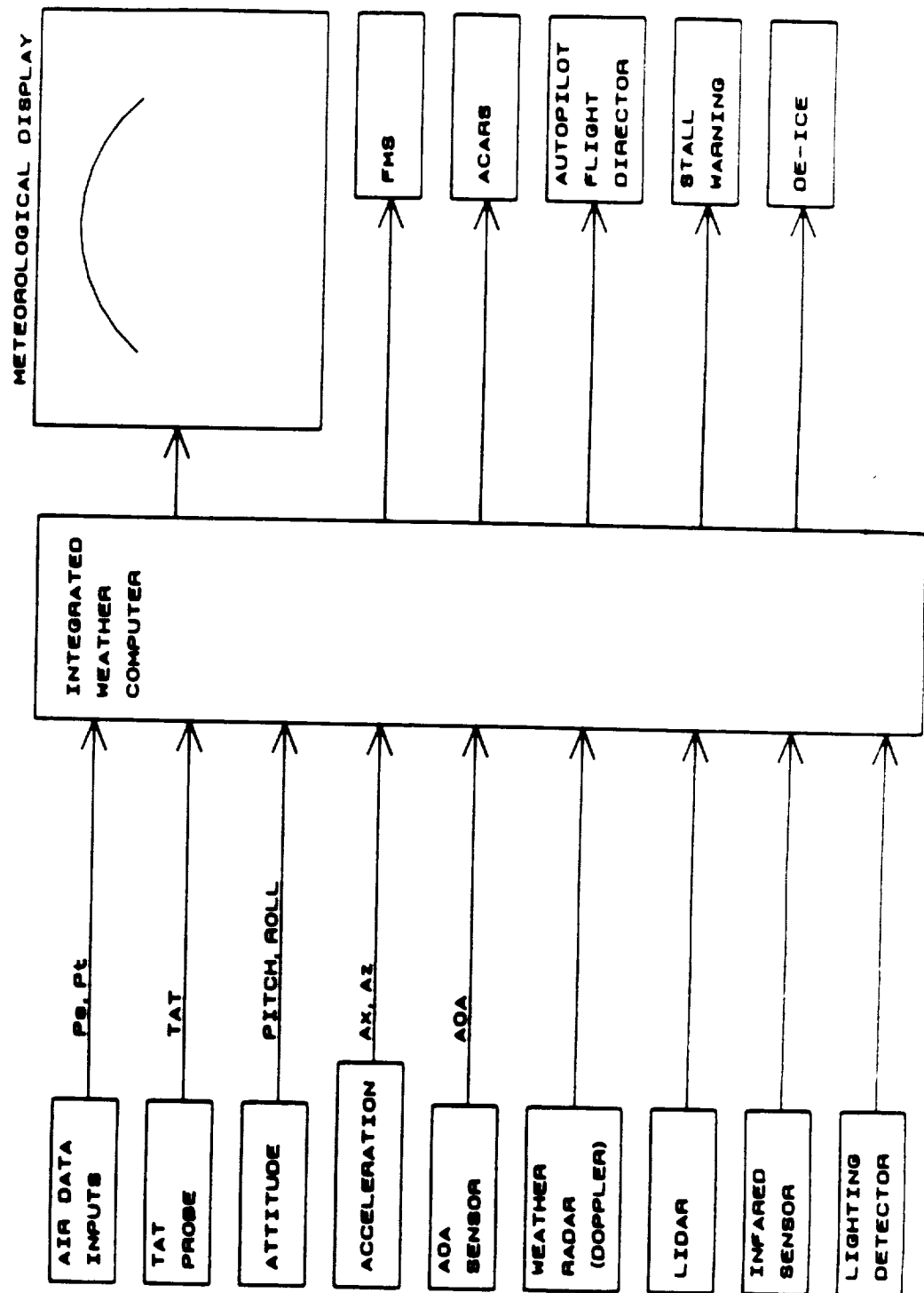
BASIC ASSUMPTIONS

- 0 INTEGRATION OF THE VARIOUS WEATHER SENSORS IS MORE ADVANTAGEOUS THAN INDIVIDUAL COMPONENTS WORKING INDEPENDENTLY.
- 0 SINGLE PROCESSING UNIT PROVIDES GREATEST CAPABILITY.
- 0 SINGLE, MULTI-FUNCTION DISPLAY IS DESIREABLE.
- 0 DISPLAY SHOULD:
 - * SHOW THE PILOT WHAT CONDITIONS ARE PRESENT.
 - * ALERT WHEN A DANGEROUS CONDITION EXISTS.
 - * PROVIDE WEATHER FORECASTING.
- 0 SYSTEM SHOULD PROVIDE OUTPUTS FOR USE BY OTHER AIRCRAFT SYSTEMS.

INTEGRATED METEOROLOGICAL SYSTEM

- 0 INTEGRATED WEATHER COMPUTER RECEIVING INPUTS FROM THE VARIOUS ATMOSPHERIC AND AIR DATA SENSORS.
- 0 EXPERT SYSTEM UTILIZING THE VARIOUS INPUTS TO PREDICT WEATHER EVENTS AS WELL AS IDENTIFY EXISTING PHENOMENA.
- 0 METEOROLOGICAL DISPLAY WITH GRAPHICAL REPRESENTATION OF THE VARIOUS WEATHER OCCURRENCES IN ADDITION TO TEXT DISPLAYS OF PERTINENT WEATHER-RELATED DATA.
- 0 OUTPUTS FOR USE BY OTHER AIRCRAFT SYSTEMS.

INTEGRATED METEOROLOGICAL SYSTEM



INTEGRATED METEOROLOGICAL SYSTEM POTENTIAL BENEFITS

O METEOROLOGICAL Display

- PROVIDE RELEVANT DATA TO THE COCKPIT.

O FLIGHT MANAGEMENT SYSTEM (FMS)

- ALTER FLIGHT PLAN BASED ON HAZARD AVOIDANCE.
- ALTER FLIGHT PLAN BASED ON DETECTED WINDS WHICH MAY REPRESENT A PERFORMANCE INCREASE.

O GROUND COMMUNICATION (ACARS)

- AUTOMATIC COMMUNICATION OF ATMOSPHERIC DATA TO GROUND STATIONS FOR SUBSEQUENT RELAY TO OTHER AIRCRAFT WHICH MAY ENCOUNTER DETECTED HAZARDOUS CONDITIONS.

INTEGRATED METEOROLOGICAL SYSTEM
POTENTIAL BENEFITS (CONT.)

O AUTOPILOT/FLIGHT-DIRECTOR

- PROVIDE GUIDANCE TO AVOID/ESCAPE A HAZARDOUS WEATHER CONDITION.

O STALL WARNING

- AUTOMATIC ADJUSTMENT OF STICK-SHAKER AOA BASED ON RAIN RATE.

O DE-ICE/ANTI-ICE

- AUTOMATIC ACTIVATION OF DE-ICE AND ANTI-ICE EQUIPMENT WHEN ICING CONDITIONS EXIST.

O ETC..

INTEGRATED METEOROLOGICAL SYSTEM EXPERT SYSTEM

THE EXPERT SYSTEM RESIDING IN THE WEATHER COMPUTER WILL PERFORM ANALYSIS OF CURRENT INPUTS TO DETERMINE IF HAZARDOUS ATMOSPHERIC CONDITIONS ARE PRESENT:

- 0 WINDSHEAR
- 0 UNSTABLE AIRMASS
- 0 HEAVY RAINFALL
- 0 TURBULENCE
- 0 LIGHTNING
- 0 STRONG WINDS

THE SYSTEM WILL ALSO PROVIDE A PROBABILISTIC ANALYSIS OF CURRENT CONDITIONS IN ORDER TO PREDICT THE LIKELIHOOD OF THE AIRCRAFT ENCOUNTERING AN UNSAFE SITUATION IN THE CURRENT FLIGHT PATH.

INTEGRATED METEOROLOGICAL SYSTEM DISPLAY

THE MULTI-FUNCTION, METEOROLOGICAL DISPLAY WILL PROVIDE PERTINENT ATMOSPHERIC DATA TO THE COCKPIT IN A CONCISE, INFORMATIVE MANNER USING GRAPHICAL, TEXT, AND PICTORIAL FORMATS.

- 0 DISPLAY FORECASTED WEATHER CONDITIONS.
- 0 DISPLAY OF CURRENT ATMOSPHERIC STATUS IN THE IMMEDIATE VICINITY OF THE AIRCRAFT.
- 0 DISPLAY OF DETECTED WEATHER CONDITIONS.
- 0 ALERT OF CONDITIONS WARRANTING IMMEDIATE PILOT ATTENTION (E.G. WINDSHEAR).

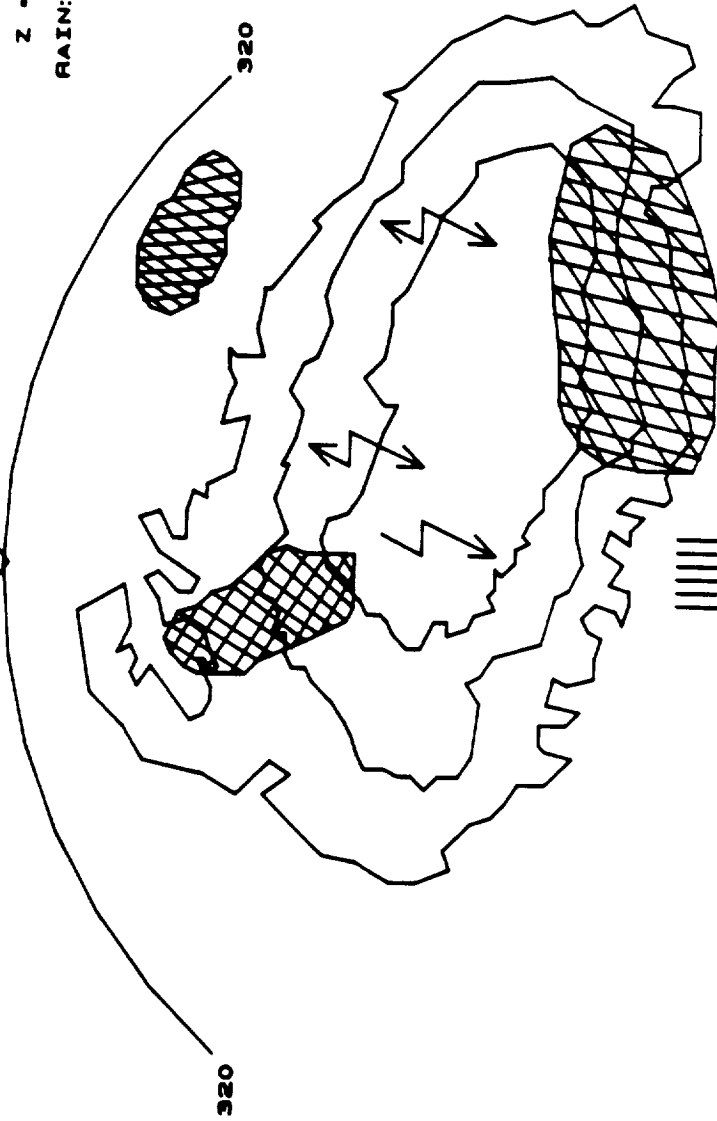
METEOROLOGICAL DISPLAY

GS 148
TAS 150

WINDSHEAR

HDG 061 MAG

WINDS:
X = 4
Y = -2
Z = -4
RAIN: 0.5



CURRENT CONDITIONS:
ICING
THUNDERSTORMS

FORECAST:
WINDSHEAR-47%
TURBULENCE-81%

SUMMARY

- 0 CURRENT EMPHASIS IS INDIVIDUAL SENSORS WHICH DETECT ATMOSPHERIC CONDITIONS.
- 0 NEXT-GENERATION IMPLEMENTATION:
 - INTEGRATION OF THE MULTIPLE SENSORS.
 - * MAXIMIZES THE BENEFITS OF EACH.
 - * MINIMIZES THE INDIVIDUAL SHORTCOMINGS.
 - * SUPPORTS COHERENT, MULTI-FUNCTION DISPLAY TECHNIQUES.
 - * PROVIDES ADDITIONAL CAPABILITIES.

Integration of Weather Sensing Devices - Questions and Answers

Q: BERNARD SILVERMAN (Active EO Systems Analyses) - What is the basis for the statement that LIDAR is poor in rain? Is there any good data?

A: JIM DAILY (Honeywell Sperry) - The ranking of LIDAR as "poor" in rain is due to information based on the Lockheed CO₂ laser. The signal is absorbed by rain and therefore the signal is significantly attenuated. This translates to a loss of range during severe rain conditions. The majority of data supporting this is as presented in Russel Targ's presentation. "Poor" only relates to the ability of the LIDAR system to penetrate heavy rain, not its ability to identify the edge of the hazard.

Session IV. Sensor Fusion & Flight Evaluation

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NASA Langley Flight Test Program
Mike Lewis, NASA Langley

NASA/LANGLEY RESEARCH CENTER

WINDSHEAR FLIGHT PROJECT

GENERAL OVERVIEW

**MICHAEL S. LEWIS
WINDSHEAR FLIGHT TEST
PROJECT ENGINEER
10/16/90**

OUTLINE

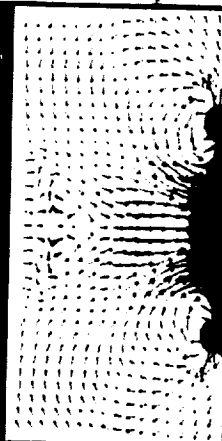
- **PROGRAM OVERVIEW**
- **FLIGHT TEST OBJECTIVE**
- **FACILITY**
- **FLIGHT REQUIREMENTS**
- **FLIGHT OPERATIONS**
- **STATUS/SCHEDULE**

NASA

L-90-1293

NASA/FAA AIRBORNE WIND SHEAR PROGRAM ELEMENTS

Hazard Characterization



- Wind Shear Physics/Modeling
- Heavy Rain Aerodynamics
- Impact on Flight Characteristics

Sensor Technology



- 2nd Generation Reactive
- Airborne Doppler RADAR/LIDAR
- Airborne Passive INFRARED
- Sensor Information Fusion
- Flight Performance Evaluation

Flight Management Systems



- System Performance Requirements
- Guidance Display Concepts
- TDWR Information Data Link Display
- Pilot Factors Procedures

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FLIGHT TEST OBJECTIVE

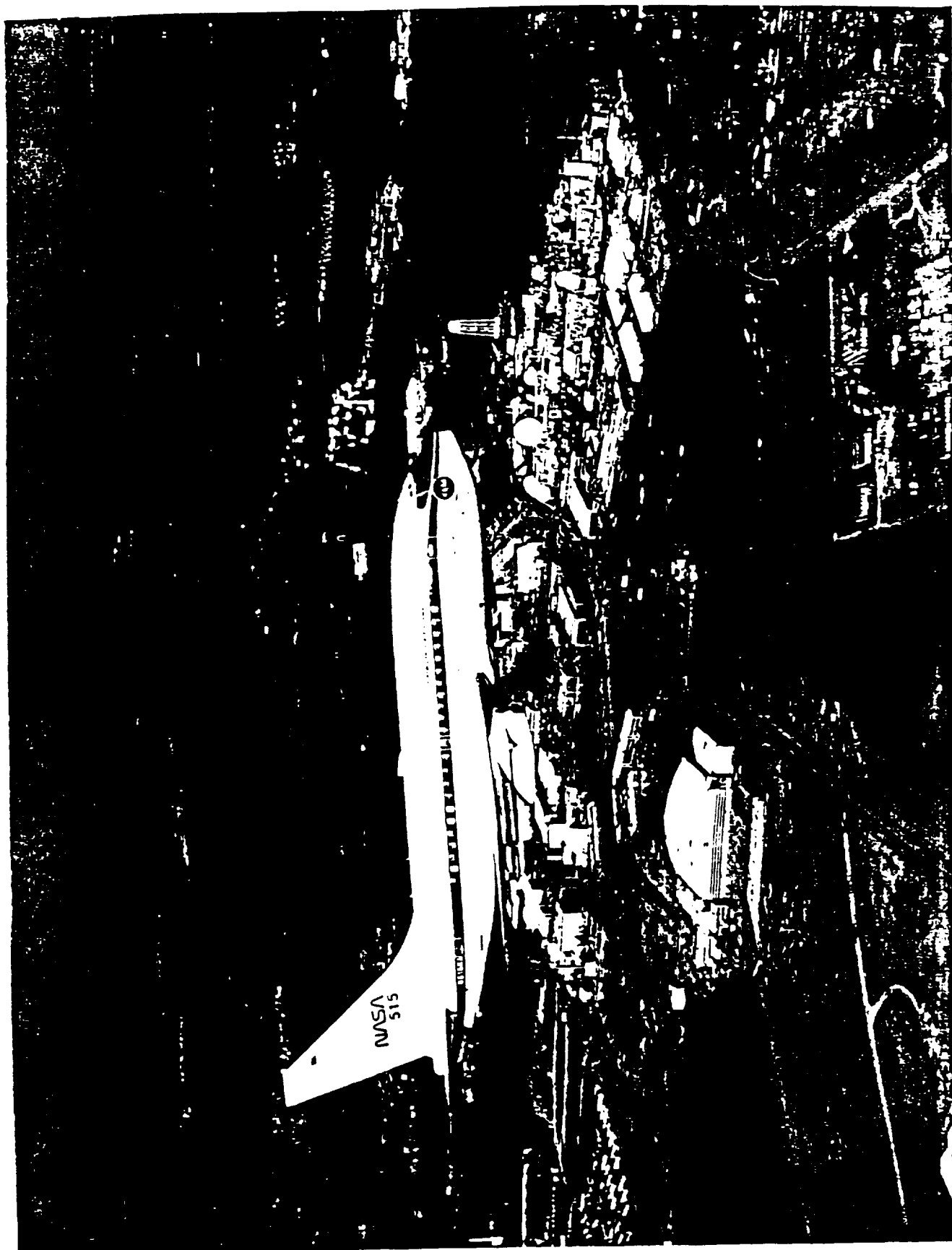
Safely
develop, refine, validate and demonstrate
advanced windshear sensor technologies and
associated pilot/vehicle interface
in a representative range of
meteorological and other operational environments
and in a timely, cost effective manner.

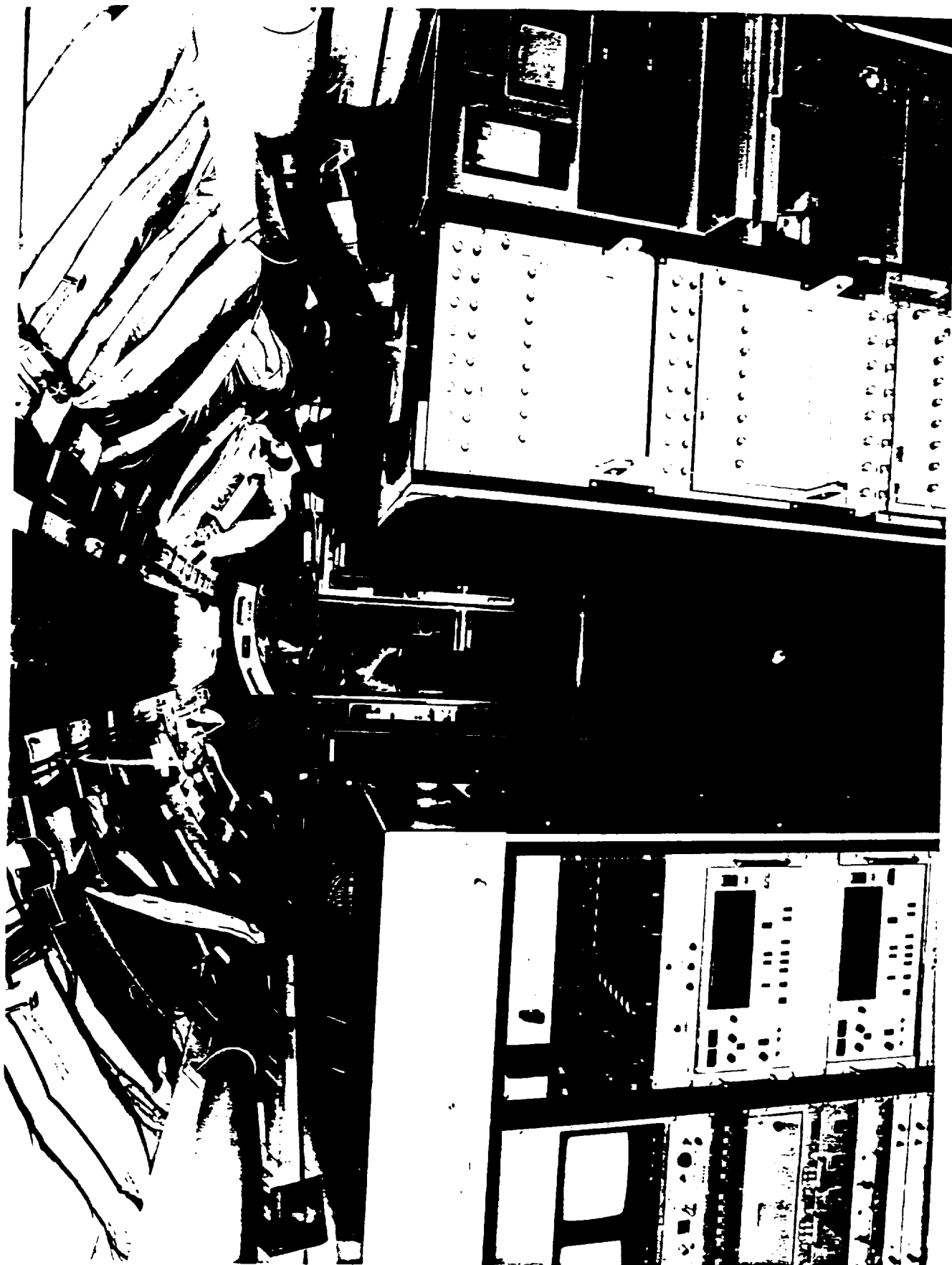
DEFINITIONS

- **safety:** No additional risk to aircraft or crew than current ATOPS/airline operations
- **validate:** Establish final performance levels against functional requirements and success criteria for each sensor subsystem.
- **demonstrate:** Effectively exhibit system operation and performance in flight to appropriate industry, government, and other organizations.
- **variety of advanced windshear sensor technologies:** Infrared, Doppler radar, in situ, Doppler Lidar, TDWR ground system airborne linkage
- **associated pilot/vehicle interface:** The crew warnings and displays, and guidance and control system interaction required for operational utilization of the sensor data for each sensor subsystem and practical sensor combinations.
- **representative range:** With enough variation to establish airborne system performance sensitivities to major variables and enable validation of ground simulation models.
- **timely:** On current schedule and responsive to FAA rulemaking and equipment installation timetables
- **cost effective:** On current budget

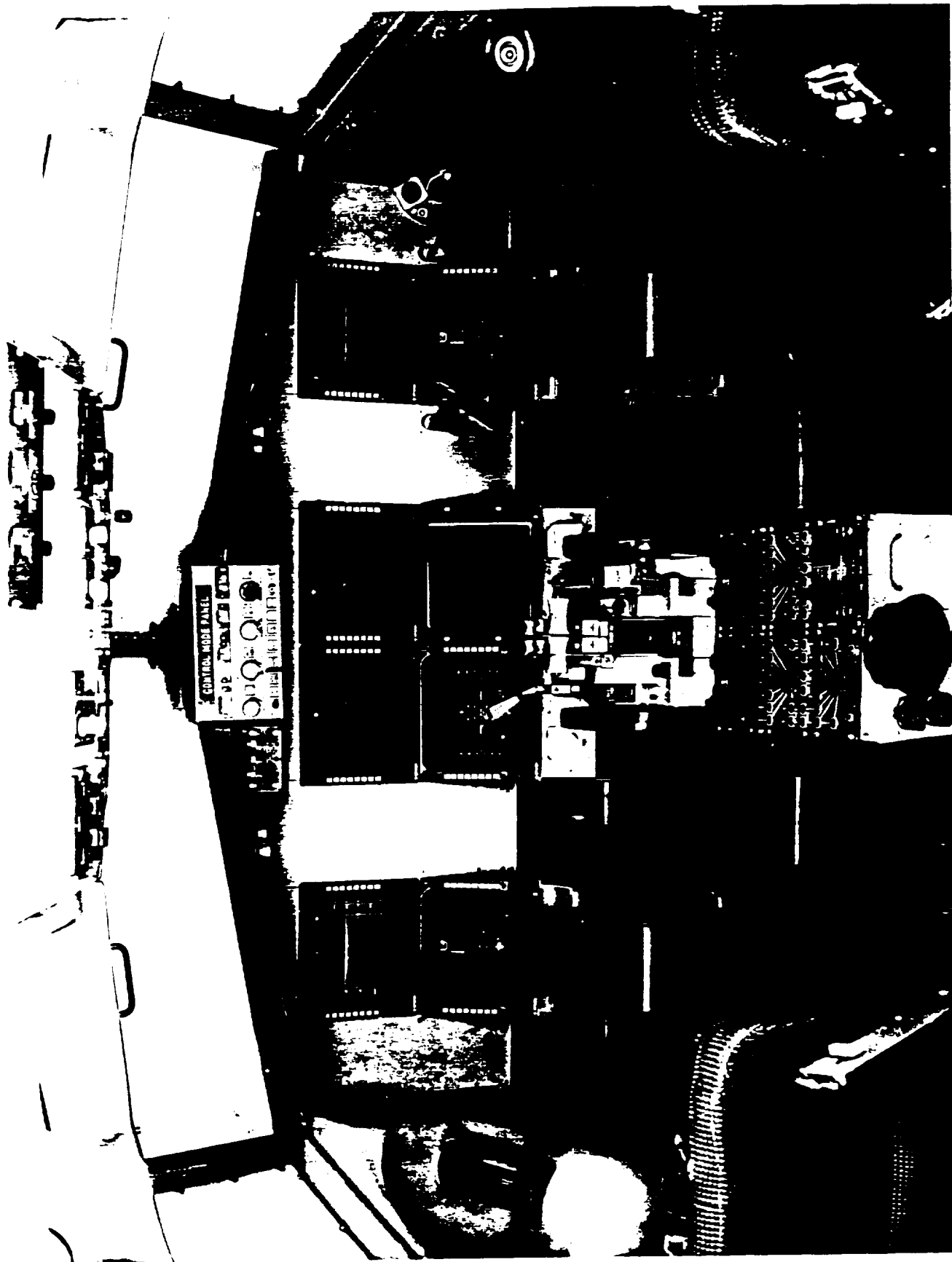
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NASA



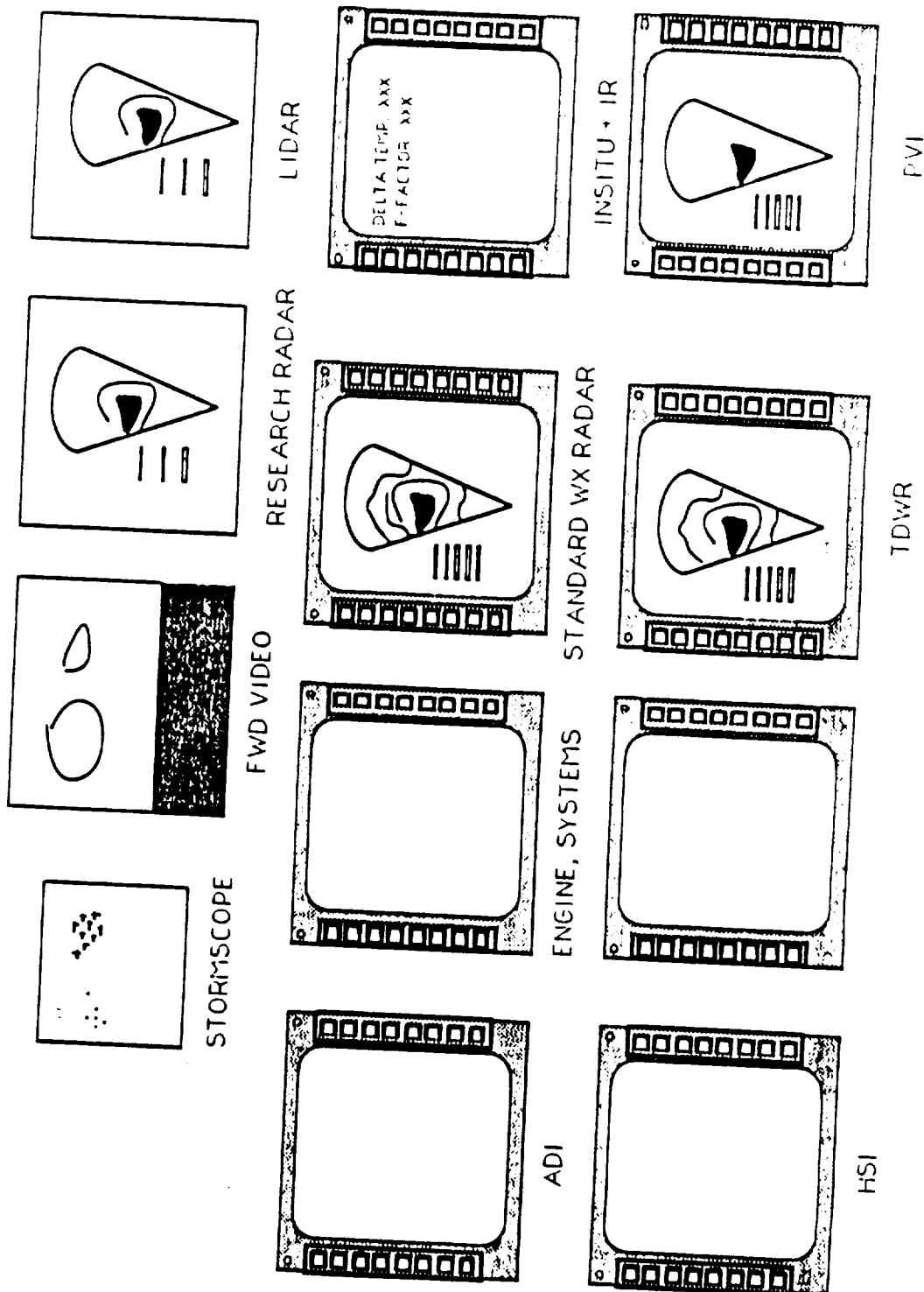


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WINDSHEAR FLIGHT PROJECT

RFD INTEGRATED MONITORING STATION



FLIGHT REQUIREMENTS

0.) HARDWARE CHECKOUT

1.) TEST TYPE I AND TYPE II ERRORS

- PROB OF DETECTION: NEED MICROBURST EVENT
- PROB OF FALSE ALARM: NEED OTHER WX, GROUND CLUTTER, A/C MANEUVERS

2.) DEVELOP AND EVALUATE TDWR DATA LINK

3.) DEVELOP AND EVALUATE PVI/SENSOR INTEGRATION CONCEPTS

4.) DEMONSTRATE ABOVE TO INDUSTRY, GOV'T, PUBLIC

5.) DO IT ON TIME

EXTERNAL EXPERIMENTAL PARAMETERS

WEATHER

- WET AND DRY MICROBURSTS (<.15 SAMPLE; >.15 STAND-OFF)
- GUST FRONTS (MED TO STRONG)
- SEA BREEZES (MED TO STRONG)
- RAIN (HIGH HUMIDITY TO 60 DBZ)
- TURBULENCE (LIGHT TO MODERATE)
- INVERSIONS (MODERATE TO STRONG)

A/C MANEUVERS

- NORMAL TAKEOFFS AND APPROACHES
- LEVEL AND TURNING FLIGHT ACCELERATIONS
- LOW LEVEL FLIGHT

GROUND FEATURES

- FIXED CLUTTER
 - MOVING CLUTTER
- (~14 DISTINCT TYPES)

TEST SITE SELECTION

THREE SITES FULFILL ALL REQUIREMENTS:

- LOCAL: CONVECTION, FRONTS, SEA BREEZES, HIGH HUMIDITY, WET MICROBURSTS (STAND-OFF), RAIN, CLOUDS, CLEAR, HAZE
- DENVER: DRY MICROBURSTS, INVERSIONS, HIGH BASE ALTITUDE, LOW HUMIDITY
- ORLANDO: WET MICROBURSTS, CONVECTION, SEA BREEZES, RAIN

WINDSHEAR FLIGHT PROJECT

MICROBURSTS/GUST FRONTS
ORLANDO, FL
6/2 - 7/13, 1990

S	M	T	W	T	F	S	
10/3	6/1	18/1	11/1	8/1	7/2	4/0	
0	0	0	0	0	0	9/3	
9/3	4/1	0/2	2/0	11/0	5/1	3/1	
8/2	16/3	7/4	0	0	0	10/1	
12/3	6/4	1/0	13/1	0	1/1	10/2	
9/3	15/2	0	11/3	20/5	10/2		

- MICROBURSTS
6 WEEKS; 256 TOTAL; 6.2 DAY; 4.8 DAYS/WEEK
- GUST FRONTS
6 WEEKS; 55 TOTAL; 1.3/DAY; 4.3 DAYS/WEEK
- DENVER DATA SIMILAR

FLIGHT OPERATIONS OVERVIEW

FLIGHT REQUIREMENT

- 0.) H/W CHECKOUT
- 2.) TEST TDWR DATA LINK
- 3.) TEST PVI CONCEPTS
- 4.) DEMONSTRATE

FLIGHT OPERATIONS REQ'T

- 0.) FLIGHT TIME ONLY
- 2.) FLIGHT TIME ONLY
- 3.) FLIGHT TIME GENERALLY
- 4.) FLIGHT TIME GENERALLY

THE REAL PROGRAM CHALLENGE. . .

- 1.) TEST FOR TYPE I
AND TYPE II ERRORS

- 1.) WEATHER, TIMING,
PERFORMANCE,
COMMUNICATIONS,
PLANNING AND
PREPARATIONS

TYPE I, II ERROR TESTING

- NEED TO CONFIRM PREDICTED MEASUREMENTS (INCLUDING TDWR) WITH A/C IN SITU DATA
 - MICROBURST MEASUREMENT REQUIRED
 - STATISTICAL SAMPLING IMPRACTICAL AND UNNECESSARY (GROUND SIMULATION ROLE)

GOAL IS HANDFUL OF SUCCESSFUL PREDICTIONS
WITH RIGOROUSLY TESTED LOW FALSE ALARM RATE

- 3 DIFFICULTIES
 - NEED WEATHER COORDINATION
 - NEED SAFETY PLAN
 - NEED OPERATIONS PLAN

SAFETY

GENERAL GUIDELINES

- 1.) MINIMIZE WEATHER EXPOSURE**
- 2.) ESTABLISH OPERATIONAL LIMITS AND PROCEDURES**
- 3.) MINIMIZE LIGHTNING EFFECTS**
- 4.) MAINTAIN COMMUNICATIONS WITH GROUND SUPPORT**
- 5.) FLIGHT CREW TRAINING**
- 6.) PHASED APPROACH**

SAFETY

ESTABLISH OPERATIONAL LIMITS AND PROCEDURES

Preliminary:

ALTITUDE: > 750 FT AGL WITH F-FACTOR > .10

AIRSPEED: > 200 KIAS WITH F-FACTOR > .10

F-FACTOR: WITHOUT TDWR: < .10

WITH TDWR: < .15

LIGHTNING: REMAIN CLEAR OF OBSERVED SEVERE ACTIVITY

REFLECTIVITY: < 40 DBZ

HAIL: WITHOUT TDWR: NO ANVIL UNDERFLIGHTS

WITH TDWR: NO FLIGHT THROUGH PREDICTED HAIL REGION

WEATHER RADAR: REQUIRED SCAN ALWAYS AVAILABLE TO FFD

GROSS WEIGHT: SET LIMIT IF INDICATED THROUGH SIMULATION

PROCEDURAL: FFD CONTROL FOR ALL SHEAR MEASUREMENTS

FUEL RESERVE FOR DIVERSION

PRE-FLIGHT GROUND OBSTACLE IDENTIFICATION

MEASUREMENT OF ISOLATED EVENTS ONLY, CLEAR
EXIT ROUTE IDENTIFIED

IMS AFT FLIGHT DECK MONITORING OF ALL LIMITS

SAFETY

PHASED APPROACH

- WINDSHEAR MEASUREMENTS ARE INTENDED TO INCREASE TO FULL LIMITS IN STAGES:

- 0 - 0.075
- 0.075 - 0.10
- 0.10 - 0.12
- 0.12 - 0.15

**ALL MEASUREMENTS ARE SUBJECT TO FINAL DECISION OF
THE FLIGHT CREW**

SAFETY

SUMMARY

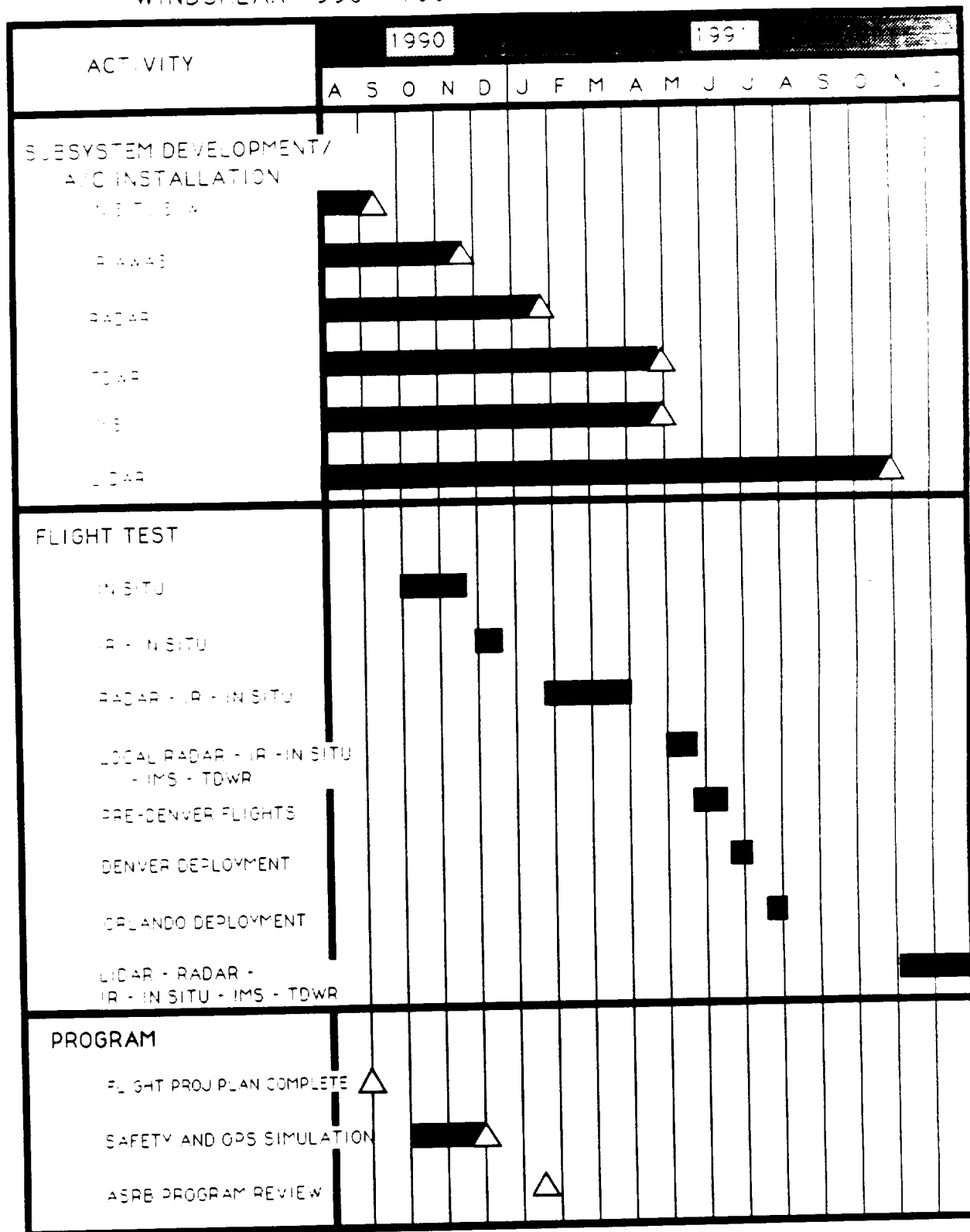
UNSAFE WINDSHEAR EXPOSURE

**FULL LANDING CONFIGURATION, APPROACH SPEED,
DESCENDING ON GLIDESLOPE, LOW ALTITUDE, DELAYS
IN RECOGNIZING SITUATION**

NASA 515 FLIGHT TESTS

**CLEAN A/C CONFIGURATION, SUBSTANTIAL EXCESS SPEED,
LEVEL FLIGHT, HIGH ALTITUDE, WRITTEN PLAN,
FULLY BRIEFED, ANTICIPATING EVENT LOCATION SIZE, AND
SEVERITY, IMMEDIATE RECOGNITION OF CONDITIONS,
EXIT PROCEDURES KNOWN IN ADVANCE**

WINDSHEAR 1990 - 1991 FLIGHT PROJECT SCHEDULE



NASA Langley Flight Test Program - Questions and Answers

Q: WALT OVEREND (Delta Airlines) - How do you judge go, no go decisions on the airplane before you penetrate a microburst? What parameters are you working from?

A: MIKE LEWIS (NASA Langley) - We establish a reflectivity limit over which we won't go through and we'll use the standard weather radar for that function. There will be a fairly rough reflectivity limit corresponding to the red level on the standard radar which is about 40 to 50 dBZ. For lightning avoidance, in general we're not going to stay away from all lightning but certainly areas of severe lighting activity we will avoid. For that we will use a lightning detector storm scope to be installed on the aircraft. We will be operating at locations covered by TDWR and will be relying on up linked TDWR information to determine whether or not the microburst strength is over the penetration threshold. We will also use their support for hail detection and avoidance in addition to the standard weather radar for that function. Additionally, we will have a number of wind shear sensors on the aircraft and to the degree that we have some operational confidence in those sensors we'll also use those, albeit research pieces of equipment for determining the limits over which we won't fly through. Lastly, there is pilot's discretion, everything is up to the guy in the front flying the airplane and anything that he's not comfortable flying through, for whatever reason, the airplane won't go through.

Q: UNKNOWN - In regard to a lot of the accidents we've seen, the encounters are down around 500 to 300 feet, as you go on with your test program are you planning on trying to gather data down there, especially for the radar sensors?

A: MIKE LEWIS (NASA Langley) - Yes. The information I presented as to what our final altitude limit will be was preliminary. That's still to be determined. We will be determining that from the piloted simulations through the microburst models which will show what kind of safety margins we have. However, I think as a general philosophy, we don't need to be operating exactly on approach in the same configuration that a real encounter would be. For test purposes, all we need to do is verify the function of the experimental systems that we have on board. So we want to fly low enough to get a healthy enough horizontal component of the shear but not necessarily put ourselves in a situation where we're flying through the maximum of that horizontal component down at the 200, 300 foot level. So as long as we stay within a band that has enough of the horizontal exposure and not totally a vertical component of the microburst we believe that we can evaluate the function of these various instruments.

ROLAND BOWLES (NASA Langley) - We've taken great pains in both of the pulse Doppler systems to provide pointing capability. When we are at 1500, in that vicinity, our problem is to keep range gates out of the ground. We are probing all the way down. The idea is to manage the antenna tilt in such a way as to not process range gates that are intersecting the ground and picking up clutter, both moving and fixed. The point is the remote sensors will be able to probe down. We can point the sensors, and we can slew the sensors. It's not necessarily confined to looking in a very narrow cone in front of the airplane.

UNKNOWN - I understand the safety constraints on that from the flight test standpoint. I guess your answer leads to more questions. You say you're already running into range problems of picking up ground clutter which are obviously going to get worse the closer along the approach or lower altitude you're at.

ROLAND BOWLES (NASA Langley) - That's the key research question we are dealing with, the whole emphasis in the radar develop program. The key thing is managing antenna tilt in such a way that along with clutter suppression techniques at the signal processing we can detect the wind shear, while de-emphasizing the contaminating effects of ground clutter. That's the research question. If we can't solve that problem then radar is not a suitable solution. We think we can by managing antenna tilt as a function of altitude, always keeping the 3 db point of the antenna out of the ground. The trade off is, we don't want to do that in such a way as to overlook the top of the outflow and therefore underestimate the threat. That's the trade off. And the best way we get the answer to those questions is to configure the system, fly and evaluate.

Q: UNKNOWN - Isn't there an obvious advantage to a ground based LLWAS type approach over the airborne equipment in avoiding the look down clutter problem?

ROLAND BOWLES (NASA Langley) - I would think so because they're on the ground. You're at least looking up a bit with your narrow beam antenna. These guys have spent considerable effort, time, resource, money and agony, no doubt, in solving the clutter return question. It's not a question of ground versus air. The policy has been set. There shall be 47 radars deployed at major TCAs and there is an airborne equipment rule. The point is, what is the airborne equipment technology that best does the job for the least amount of bucks and makes incremental improvements in safety. I don't know what the answer to that question is but we think we'll have more information to draw inference on it after we finish our flight program with these three sensors.

UNKNOWN - Again, 750 feet seems a bit high. I'm still concerned about the issue of where the down flow becomes outflow and to the extent that you are almost at that transition altitude and that you are looking at pilot technique above and beyond the sensors, or the pilot's ability to interface with the information in the flight deck. That's been an area of difficulty, as you know for us, in the development of the wind shear training aid and pilot technique and so forth, to recognize the safety concerns. But it does seem there is area below 750 feet that needs exploration.

ROLAND BOWLES (NASA Langley) - In the NASA program we're not looking at pilot technique. We're using the airplane as a platform to hold the sensors. We're not looking at recovery techniques or anything like that. Based on the totality of data obtained over the many years of the test program the maximum outflow is, statistically, somewhere between 80 and 150 meters altitude and the half velocity point is 300 to 400 meters typically. So there is plenty of signal and outflow aloft based on, I would think now, hundreds of measurements of microburst.

MIKE LEWIS (NASA Langley) - The preliminary limits that I was showing are only applied when we've got a microburst out there that's over our threshold limit, the threshold being around 0.1 or so. We will then impose a minimum altitude constraint. Below that threshold we'll fly all the way down to touchdown. These sensors will be operational in the research mode all the way down through touchdown even through microburst or whatever other weather phenomena below the 0.1 level threshold. So there is still the opportunity to detect and evaluate the sensor's performance all the way down to touchdown within the flight test program.

BILL MELVIN (Airline Pilots Association) - I've got to speak to this maximum outflow issue. This was an idea that was used to perpetuate the ground cushion theory myth of microburst or downdrafts. That myth was that in a downdraft you didn't have to worry about flying under it because it couldn't blow through the ground so there had to be a

cushion down there. So, over the years people developed this idea that the maximum outflow occurred somewhere around 300 feet, it's also called 100 meters. With that kind of philosophy it means that it gets better below 300 feet. Therefore, the only reason the airplane would hit the ground was that the pilot didn't fly it right. Albert Bedard and S. J. Caplan have measured the maximum outflow, it's in AIAA paper, 87-0440, and they found that in the highest velocity downdrafts the maximum outflows occurred at about 10 meters, roughly 30 feet above the ground.

ROLAND BOWLES (NASA Langley) - I agree with you Bill. I don't know exactly where it is, but I know one thing, its got to go to 0 somewhere down there. It's just a question of how thick the boundary layer is.

Session V. TDWR Data Link / Display

Session V. TDWR Data Link / Display

N91-24176

**TDWR Information on the Flight Deck
Dave Hinton, NASA Langley**

TDWR INFORMATION ON THE FLIGHT DECK

**DAVID A. HINTON
NASA, LANGLEY RESEARCH CENTER**

**THIRD COMBINED MANUFACTURERS' AND TECHNOLOGISTS'
AIRBORNE WINDSHEAR REVIEW MEETING**

**Hampton, VA
Oct 16 - 18, 1990**

BACKGROUND

- **FAA INTEGRATED WINDSHEAR PROGRAM ADDRESSES BOTH GROUND AND AIRBORNE ASPECTS OF HAZARD REDUCTION. NASA ROLE HAS BEEN IN AIRBORNE SIDE**
- **FAA EFFORTS HAVE DEVELOPED TERMINAL DOPPLER WEATHER RADAR FOR MICROBURST DETECTION - TDWR HAS PROVEN CAPABILITIES IN OPERATIONAL DEMONSTRATIONS**
- **CREW COMMUNICATIONS ISSUES HAVE SURFACED DURING DEMONSTRATIONS**
- **NASA ASKED TO EXPAND SCOPE OF EFFORT TO INCLUDE INTEGRATION OF GROUND-DERIVED WINDSHEAR INFORMATION ON THE FLIGHT DECK**

AIR / GROUND WIND SHEAR INFORMATION INTEGRATION RESEARCH

GOAL

**TO SUPPORT FAA AVIATION POLICY INITIATIVE TO REDUCE WIND
SHEAR RISK THROUGH INTEGRATION OF TDWR TECHNOLOGY AND
AIRBORNE DETECTION SYSTEM CAPABILITIES**

APPROACH

**PERFORM GROUND SIMULATIONS AND CONDUCT A SERIES OF FLIGHT
EXPERIMENTS COLLATERAL WITH AIRBORNE SENSOR
DEMONSTRATIONS AT LOCATIONS COVERED BY TDWR**

- **DETERMINE THE BENEFIT OF REAL-TIME AIRBORNE
PROCESSING OF DATA LINK TDWR INFORMATION**
- **DEVELOP EXECUTIVE-LEVEL CREW ALERTING PROTOCOLS
AND OPERATING PROCEDURES REQUIRED TO DETECT AND
AVOID WIND SHEAR**
- **DEVELOP INFORMATION-LEVEL SENSOR FUSION CONCEPTS
CONSISTENT WITH OPERATIONAL REQUIREMENTS**

AIR / GROUND WIND SHEAR INFORMATION INTEGRATION RESEARCH

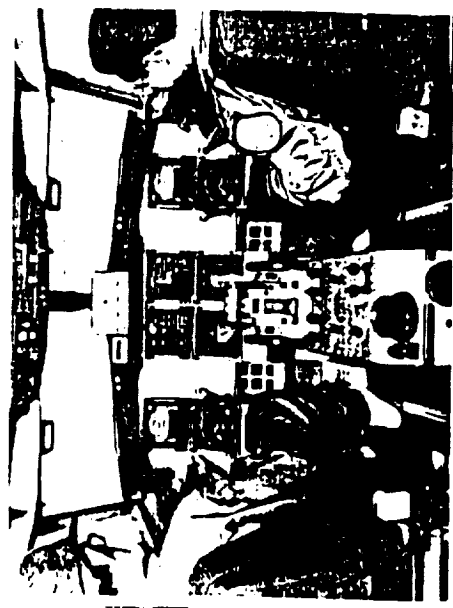
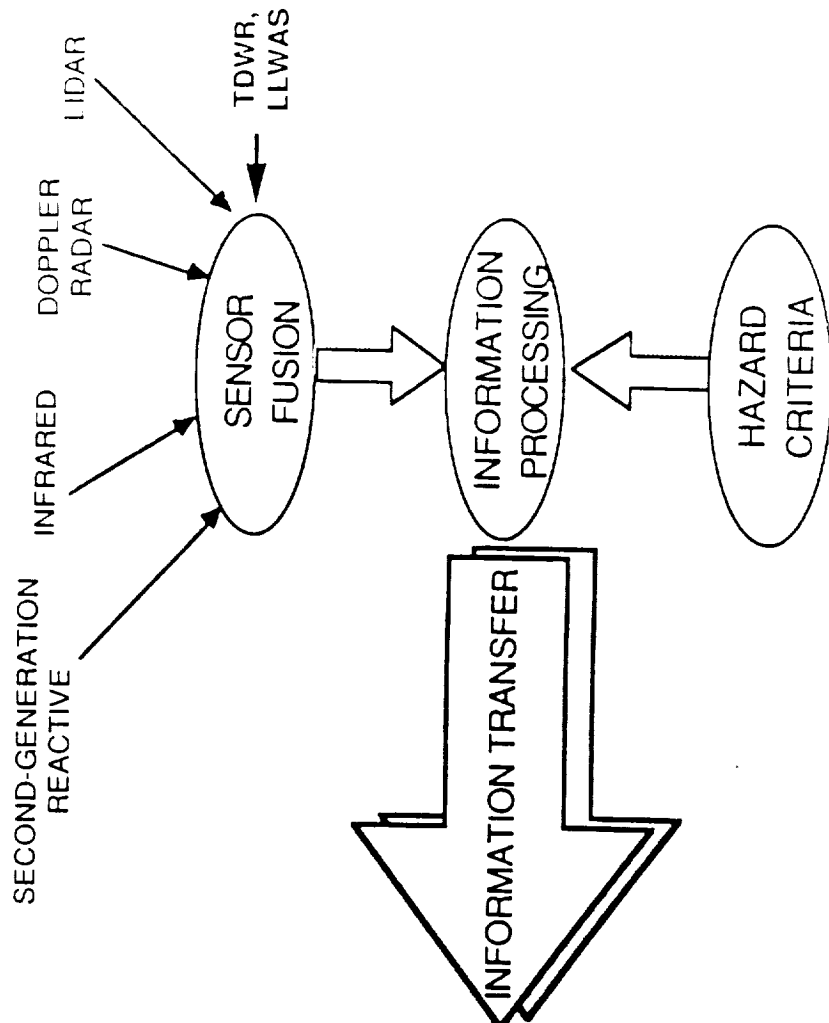
GROUND RULES

- **DON'T CHANGE THE GROUND SYSTEMS OR CURRENT ATC ROLES**
- **IDENTIFY GROUND PRODUCTS NEEDED FOR UPLINK TO SUPPORT
TIME CRITICAL INFORMATION PROCESSING AND DISPLAY**
- **DOWNLINK STATUS OF AIRBORNE WARNING TO ATC**
- **TASK TAILORED AIR / GROUND ROLES**
 - **GROUND - CLASSIFY AND LOCATE**
 - **AIRBORNE - QUANTIFY AND ANNUNCIATE**
- **KEEP OPERATIONAL PROCEDURES SIMPLE e.g., STRAIGHT UP
AND OUT AVOIDANCE**
- **FOCUS PROGRAM ON TECHNOLOGY INTEGRATION / EVALUATION**

WIND SHEAR DETECTION/WARNING AND AVOIDANCE SYSTEM

FLIGHT DECK
INTEGRATION

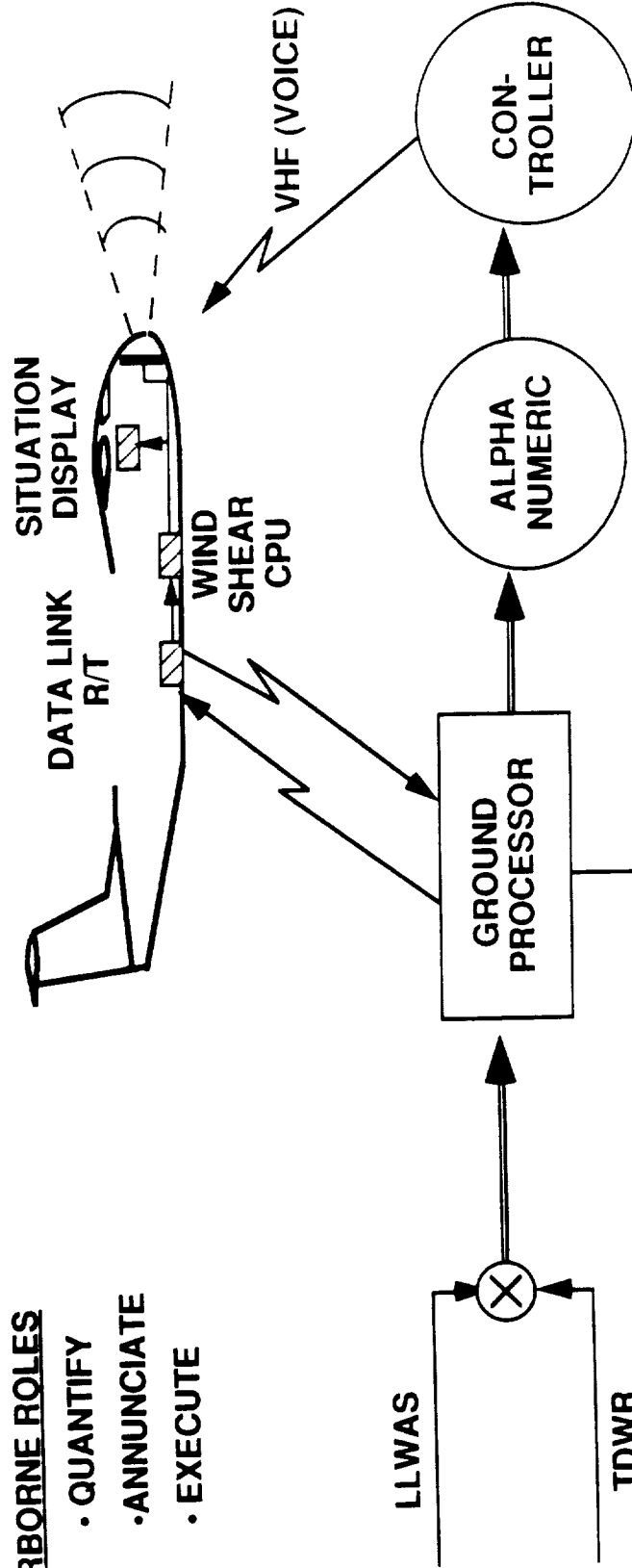
FLIGHT SYSTEMS
TECHNOLOGY



AIR / GROUND WIND SHEAR INFORMATION INTEGRATION INTEGRATION CONCEPT

AIRBORNE ROLES

- QUANTIFY
- ANNUNCIATE
- EXECUTE

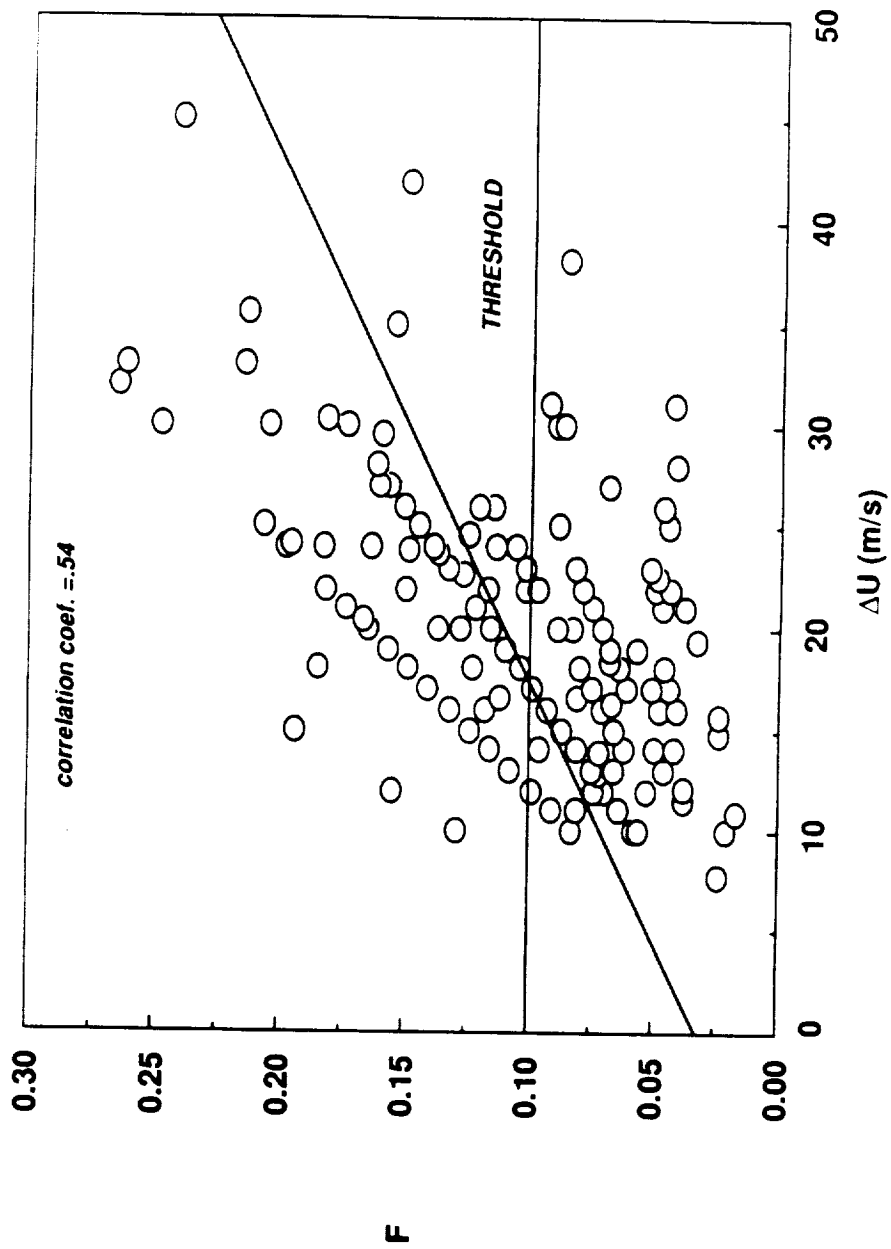


GROUND ROLES

- LOCATE
- CLASSIFY
- COMMUNICATE

TOWER SUPERVISOR

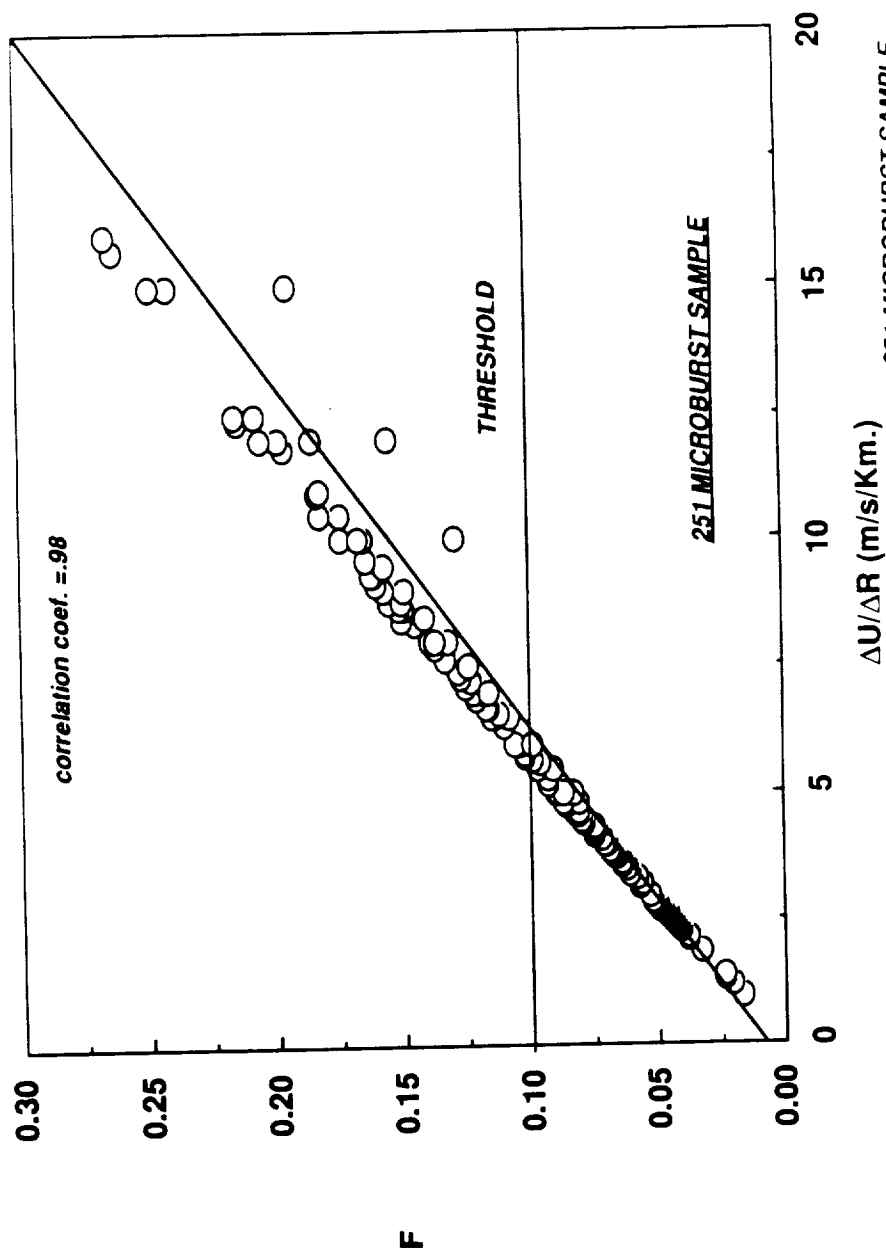
CORRELATION OF F-FACTOR WITH MICROBURST WIND DIVERGENCE



251 MICROBURST SAMPLE

- 39 JAWS (NCAR)
- 27 FLOWS (LINCOLN LAB)
- 29 CINDE (NOAA)
- 156 DENVER TDWR (LINCOLN LAB)

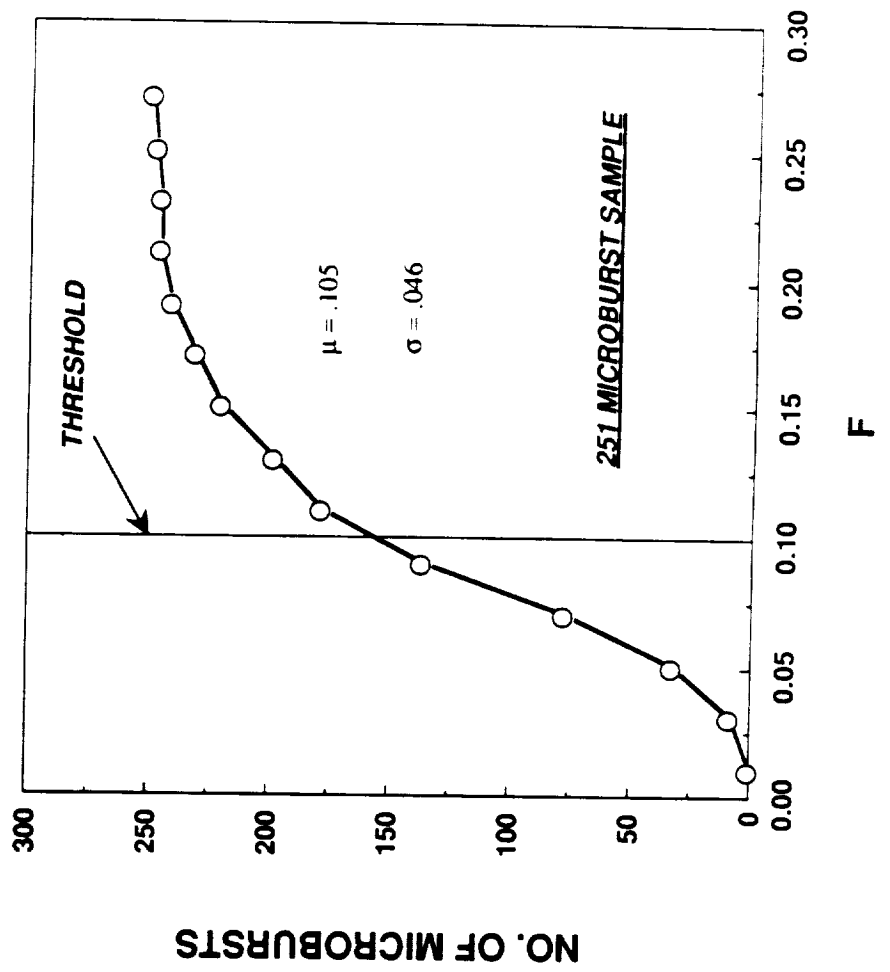
CORRELATION OF MICROBURST F-FACTOR WITH WIND DIVERGENCE MICROBURST RADIUS



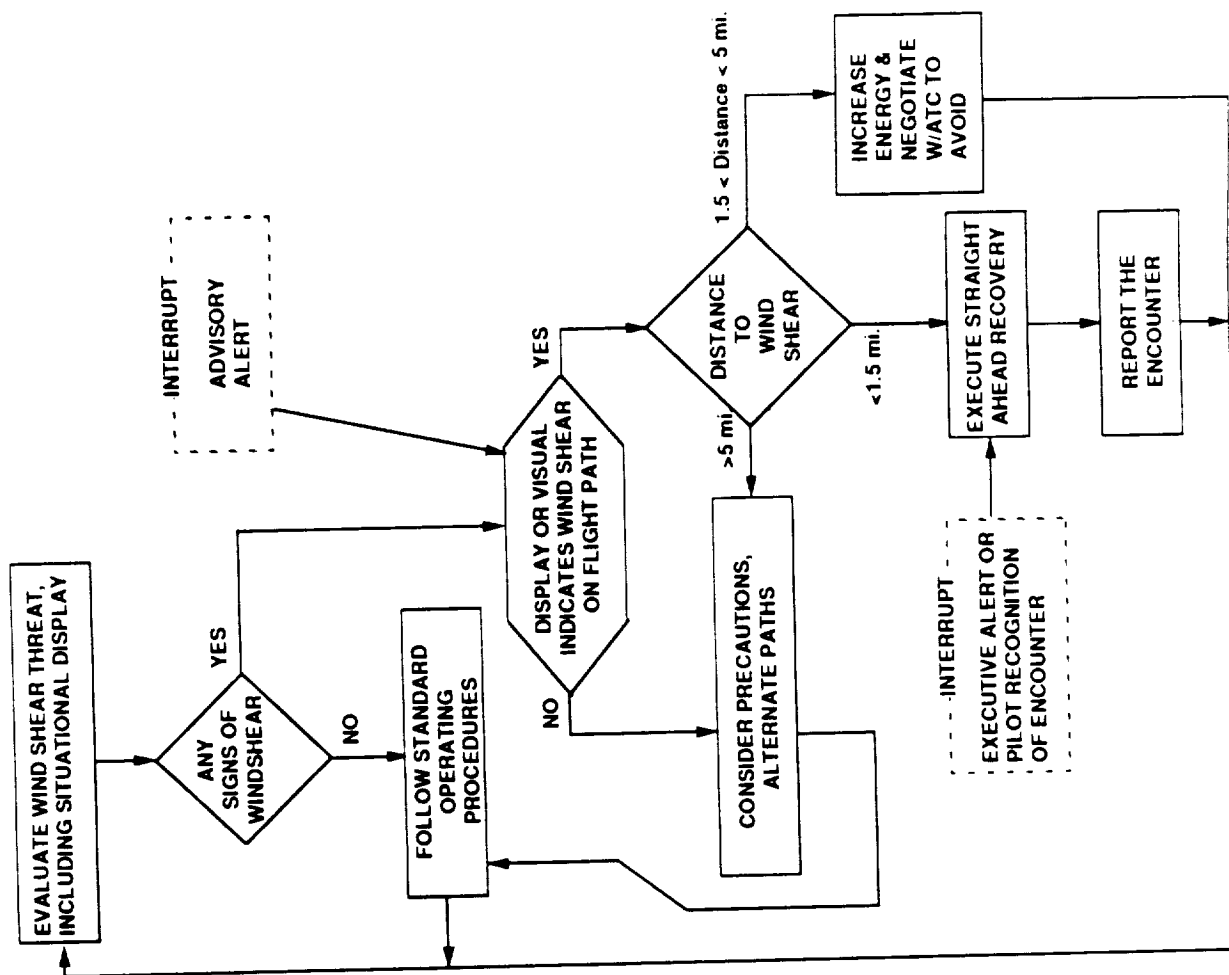
251 MICROBURST SAMPLE

- 39 JAWS (NCAR)
- 27 FLOWS (LINCOLN LAB)
- 29 CINDE (NOAA)
- 156 DENVER TDWR (LINCOLN LAB)

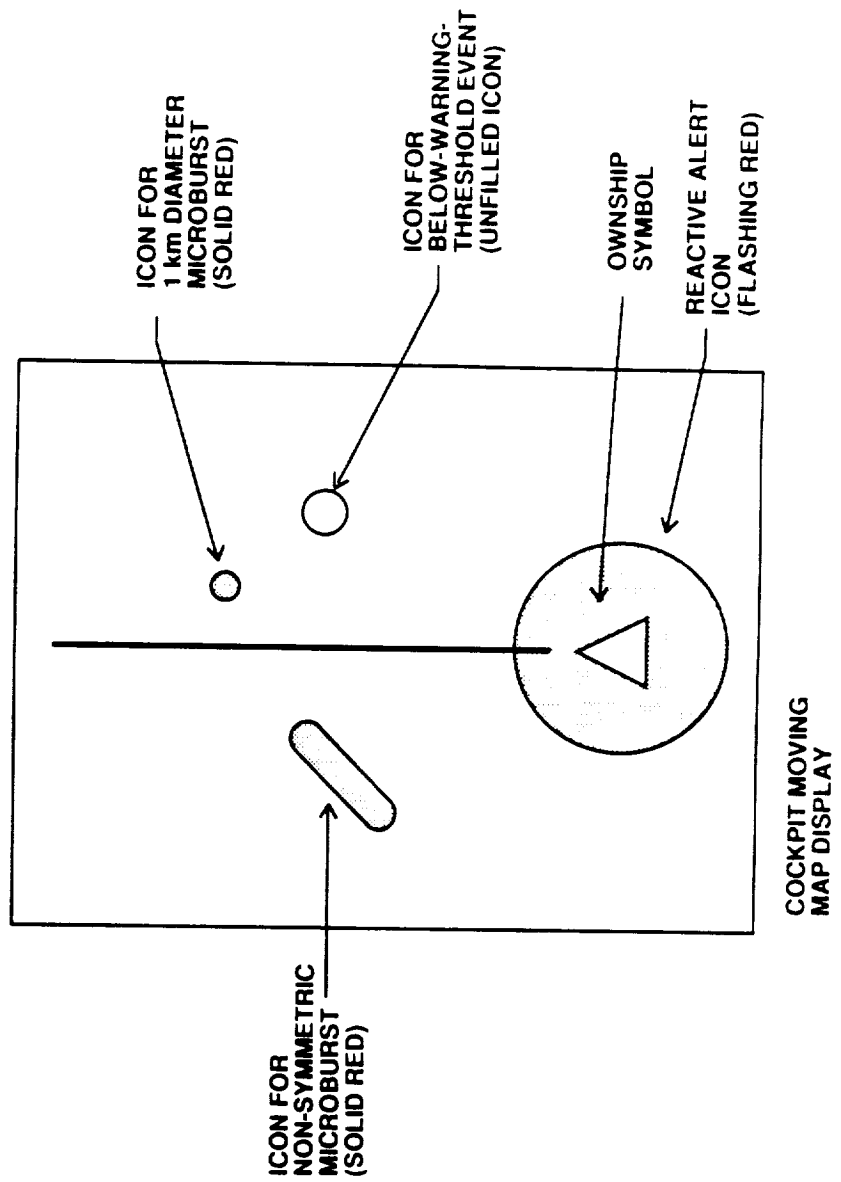
MICROBURST SAMPLE CUMULATIVE DISTRIBUTION



WINDSHEAR CREW PROCEDURE



CREW DISPLAY CONCEPT



INITIAL EXPERIMENT

- **CONDUCT FLIGHT EXPERIMENT WITH TDWR DEMO AT ORLANDO -
SUMMER 1990**
 - **CONTRACT TO MIT LINCOLN LAB**
 - **DATA LINK OF TDWR INFORMATION TO UND CESSNA CITATION**
 - **EVALUATE NASA F-FACTOR ALGORITHM FOR TDWR
APPLICATION**
 - **CORRELATE TDWR, AIRBORNE IN SITU, AND INFRARED
WINDSHEAR DATA**
- **RESULTS**
 - **NUMEROUS MICROBURSTS DETECTED BY TDWR AND
ENCOUNTERED BY CITATION**
 - **ANALYSIS OF JULY 7 MICROBURST CORE PENETRATION
SHOWED EXCELLENT AGREEMENT BETWEEN TDWR,
INFRARED, AND IN SITU F-FACTORS**
 - **ANALYSIS OF OTHER EVENTS TO FOLLOW IMPLEMENTATION
OF DATA PROCESSING AIDS**

FUTURE PLANS

- **CONDUCT ANALYTICAL AND PILOTED SIMULATION OF CANDIDATE CREW PROCEDURE**
- **REFINE F-FACTOR ALGORITHM AND HAZARD CRITERIA**
- **PROVIDE DATA LINK AND DISPLAY OF TDWR INFORMATION TO NASA B737 FOR COMBINED SENSOR RESEARCH FLIGHTS AT ORLANDO AND DENVER (NCAR & MIT LINCOLN LAB)**

TDWR Information on the Flight Deck - Questions and Answers

Q: FRED REMER (University of North Dakota) - The climatology of F-factor from JAWS, flows and TDWRs is impressive, but I'm troubled by some of the assumptions used to calculate F-factor, such as the downdraft, the true airspeed, etc. Would it make more sense to use aircraft data?

A: DAVE HINTON (NASA Langley) - Certainly, where it's available we would like to have aircraft data. The number of cases where an aircraft went through the core of a microburst while being examined by a radar is very, very small. I don't believe the true airspeed assumption is invalid, as a matter of fact, it is probably more valid to assume a typical transport category aircraft approach speed rather than the airspeed that you would go through in the Citation. You're going through quite a bit faster than a transport would. The estimation of the downdraft is obviously an area that needs more research.

Q: FRANK DREW (Lockheed Austin Division) - There is lots of looking at detection, interpretation, and integration. Basic systems such as LLWAS and TDWRs use different I/O parameters. Ground people and air crews have varying information needs. Cockpit real estate is very limited. Pilots must make their own decisions - not react to safety of flight decisions made from the ground. You say that future work includes display development. Given the situation the question is: is anyone in charge of developing cockpit display requirements, specs and standards? Should there be standardized displays? Who is in charge? What kind of aviator interaction (ALPA, airline operations people, NASA, DOD, MAC)? What kind of industry interaction? And a timetable for all of the above?

A: DAVE HINTON (NASA Langley) - I think we're getting into the realm here of the S7 committees, the various processes that are used to formulate industry specs, aviation practices and TSOs. NASA is certainly not in charge of developing display standards for the flight deck. We can provide guidelines. We can do the research to tell you what the forward looking systems are capable of doing. We can develop candidate crew procedures that can be supported by these forward looking systems. We can certainly develop display concepts and provide all the guidelines we get from research. We as an industry, again the S7, the airlines, the airframers and FAA certification, have to get together as a team to iron out the standards and specs. Timetable? I don't know. We're talking now about the formulation of an S7 committee on forward looking systems. I don't know of any being formed on displays. We'll be able to show you what you can do with a forward look system, but additional work has to be done to integrate this information with the displays given all the other requirements on the displays, such as ground prox, TCAS, etc., etc.

Q: WALT OVEREND (Delta Airlines) - You mentioned second generation reactive wind shear systems. What do you see as a better design to achieve a second generation system?

A: DAVE HINTON (NASA Langley) - I believe the current generation systems have two problems. One is a false alarm problem that can be induced by the turbulence rejection filtering that must be done, the lack of appropriate filtering or any misphasing of the various aircraft inputs. Secondly, aircraft maneuvering, thrust changes by the pilot, flap, spoilers, or gear position changes, all tend to ripple through or feed back as an F-factor on a reactive system. NASA has been involved in some simulation research over the past year and we're just now moving it into our airplane, to develop a second generation insitu system to be used as a truth measurement for our combined sensor flight test. The F-factor equation I showed this morning is a very simplified form of the F-factor and only holds true while the airplane is flying in the vertical plane. If you bank the airplane and start

turning, a lot of other parameters fall into that equation. These parameters have to be included and we're now doing that.

Q: WALT OVEREND (Delta Airlines) - Do any of the conducted studies look at prevailing atmospheric and/or geographic formation to be able to predict how rapidly microburst form and move or decay and dissipate?

A: DAVE HINTON (NASA Langley) - There is a great deal of experience and documentation on that problem. The JAWS, Flows and CINDE data, similar to what we've presented today, show the microburst to be a very dynamic event. They can grow very rapidly from an insignificant event to a full strength microburst in a 3, 4 or 5 minute period, then they tail off relatively slowly. When do they cease to be a microburst, and when do you call off the alarm, is another question. As far as one dedicated reference on that particular topic, I didn't know of any out there. But, the data is buried in a number of reports; the information is available.

Session V. TDWR Data Link / Display

N 9 1 - 2 4 1 7 7

Orlando Experiment
Dr. Steve Campbell, MIT Lincoln Laboratory

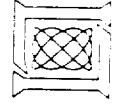
ORLANDO '90

**FAA TERMINAL DOPPLER WEATHER RADAR PROGRAM
NASA/FAA AIRBORNE WIND SHEAR PROGRAM**

STEVEN D. CAMPBELL

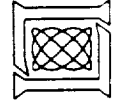
M. I. T. LINCOLN LABORATORY

17 OCTOBER 90

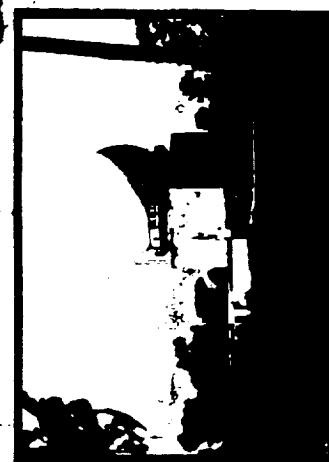
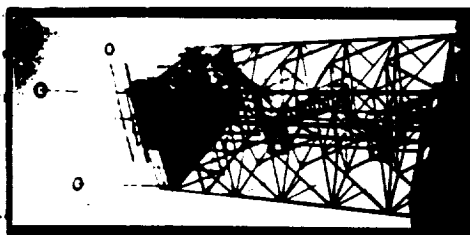
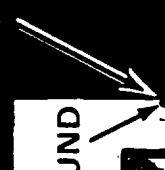


TOPICS

- **TDWR TESTBED RADAR PERFORMANCE**
- **COCKPIT DISPLAY SYSTEM**
- **FLIGHT OPERATIONS**
- **ANALYSIS WORKSTATION**
- **FUTURE WORK**



WINDSHEAR DETECTION RADAR LOCATIONS FOR 1990 TESTS IN ORLANDO



FL-2

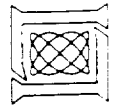
FL-3

UND

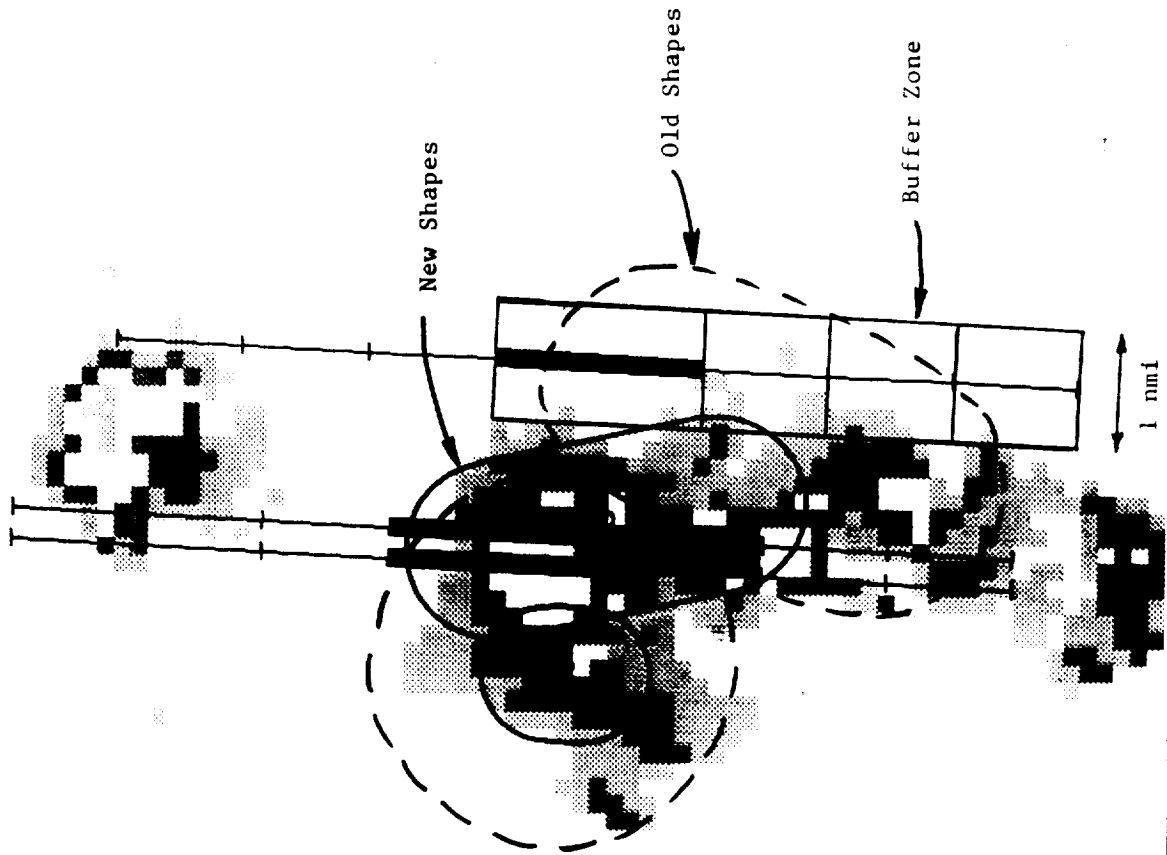
1 MILE

MICROBURST RECOGNITION

	POD	PFA
TDWR spec.	$\geq 90\%$	$\leq 10\%$
Denver '88	90%	5%
KC '89	96%	7%
Orlando '90	95%	4%



PARAMETER ADJUSTMENT



8 JUL 90 19:57:26

MICROQUEST

MODE: MAINTENANCE
GTTIME:

OF MOVEMENT:

ARCHIVE:

AUTOABLE: RANGE:

STORM MOTION: MB PREDICT:

PRECIP:

17A	WSA 25k- RWY	Calm
17D	WSA 25k- RWY	Calm
35A	WSA 25k- 1MF	Calm
35D	WSA 25k- RWY	Calm
181A	WSA 25k- RWY	030 05
181D	WSA 25k- RWY	340 04
36RA	WSA 25k- 2MF	340 04
36RD	WSA 25k- RWY	030 05
18RA	WSA 25k- RWY	030 05
18RD	WSA 25k- RWY	340 04
36LA	WSA 25k- 2MF	340 04
36LD	WSA 25k- RWY	030 05

8 JUL 90 19:57:26

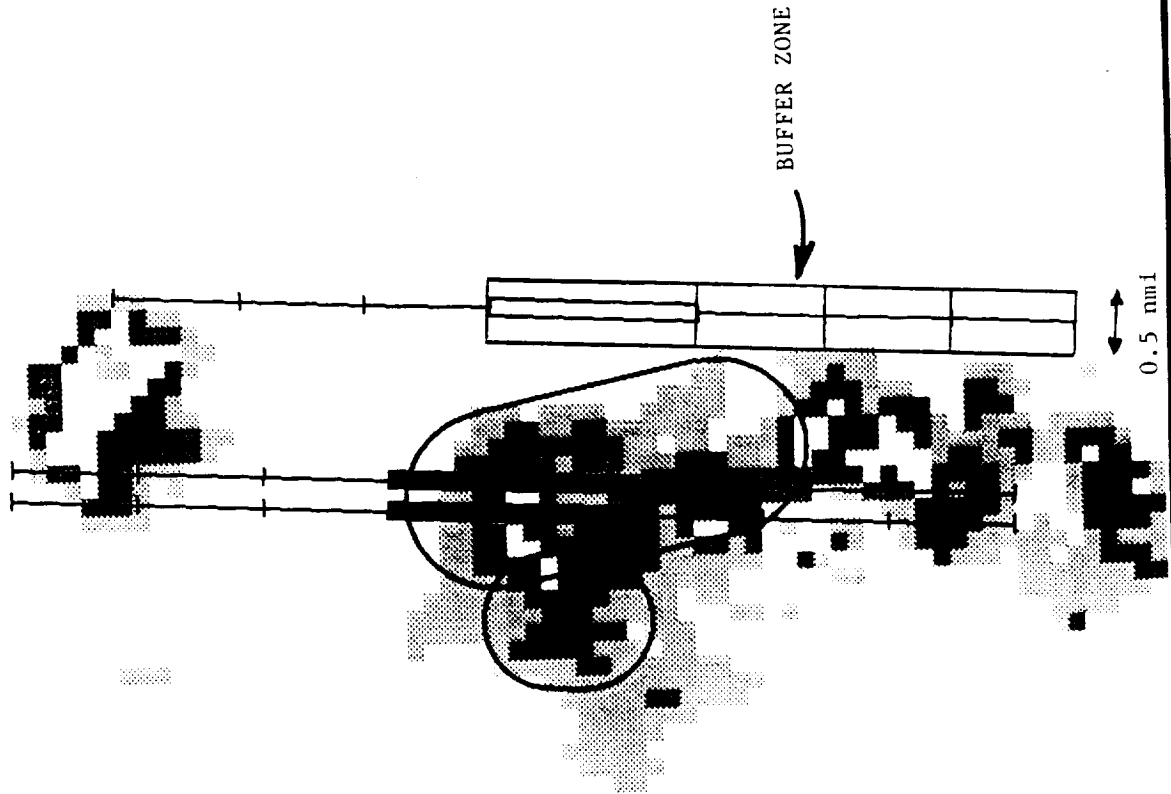
MICROBURST

MODE: MAINTENANCE
GTONE:

GF MOVEMENT: AIRPORT
ARCHIVE: READY 12 HRS REMAIN
AUDIBLE: OFF RANGE: 5NM
STORM MOTION: ON MB PREDICT: ON
PRECIP: 3 4

17A	340 04	Calm
17D	050 03	030 05
35A	050 03	030 05
35D	340 04	Calm
18LA	WSA 25K- RWY	Calm
18LD	WSA 25K- RWY	030 05
36RA	WSA 25K- 2MF	030 05
36RD	WSA 25K- RWY	Calm
18RA	WSA 25K- RWY	Calm
18RD	WSA 25K- RWY	030 05
36LA	WSA 25K- 2MF	030 05
36LD	WSA 25K- RWY	Calm

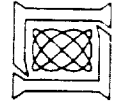
BUFFER ZONE ADJUSTMENT



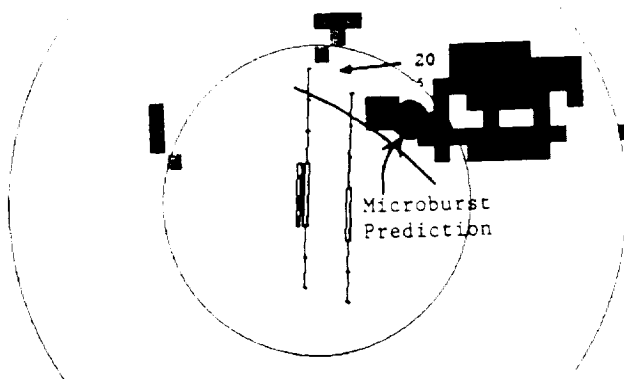
OVERLAY RUNWAY CLEAR

MICROBURST PREDICTION

	POD (≥ 15 m/s)	PFA (< 10 m/s)	Warning (min.)
KC '89	61%	11%	5.0
Orlando '90	56%	7%	6.4
Mean	59%	9%	5.7

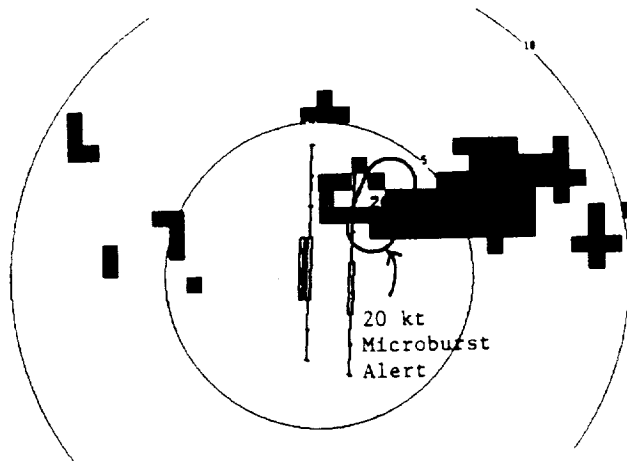


(a)



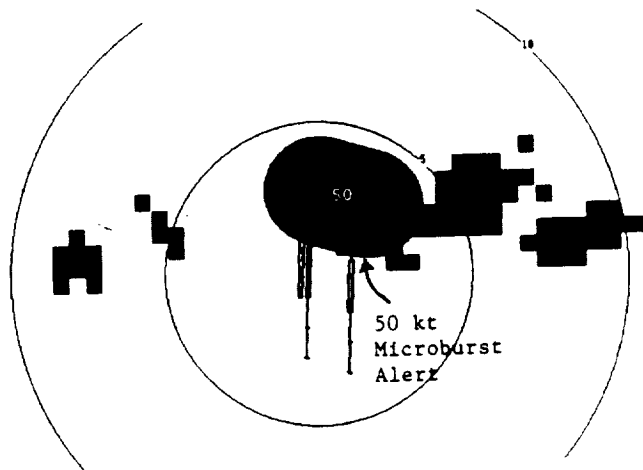
1843 (UT)

(b)



1850 (UT)

(c)



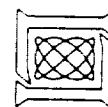
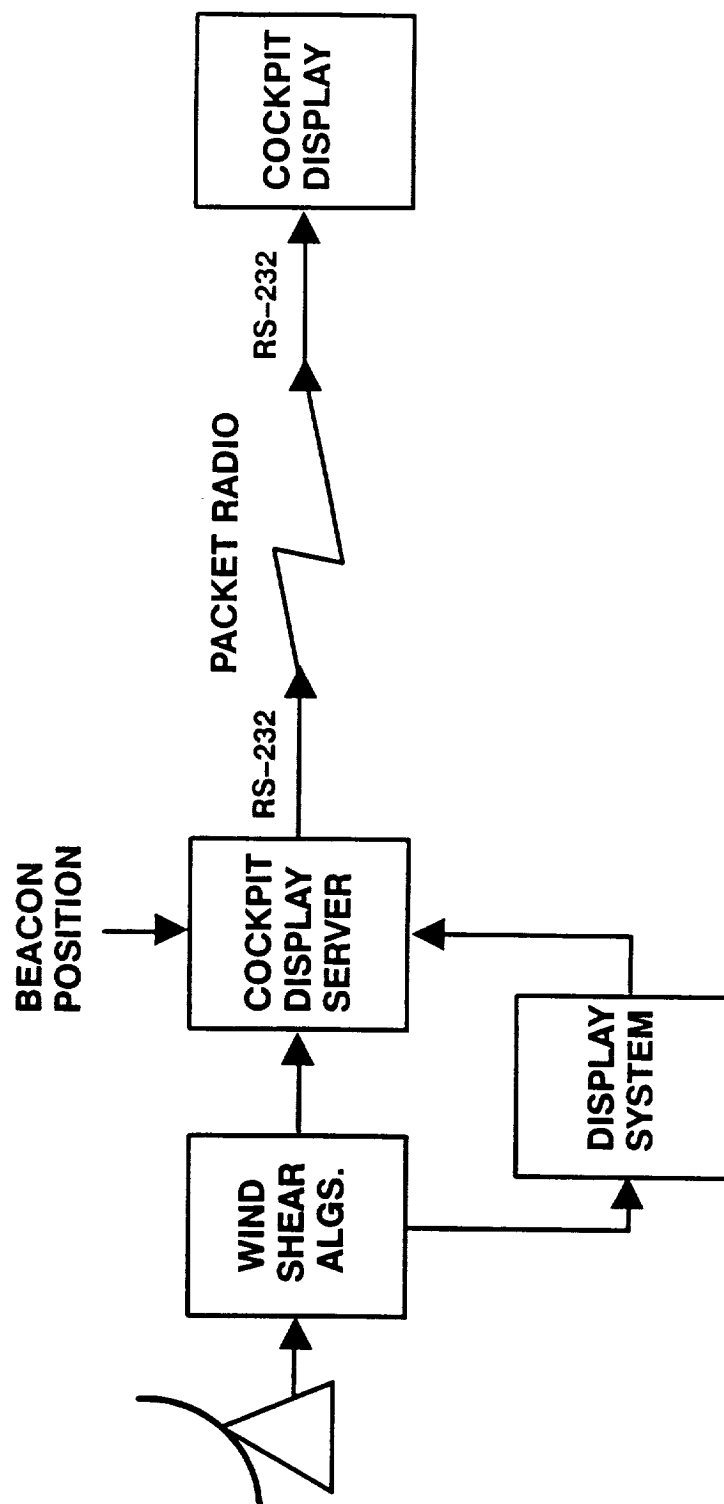
1855 (UT)

Figure 1. Microburst prediction example for July 7, 1990

COCKPIT DISPLAY SYSTEM

TDWR TESTBED RADAR

CITATION AIRCRAFT



COCKPIT WIND SHEAR DISPLAY
(MODIFIED ARGUS 5000)

ARGUS 5000

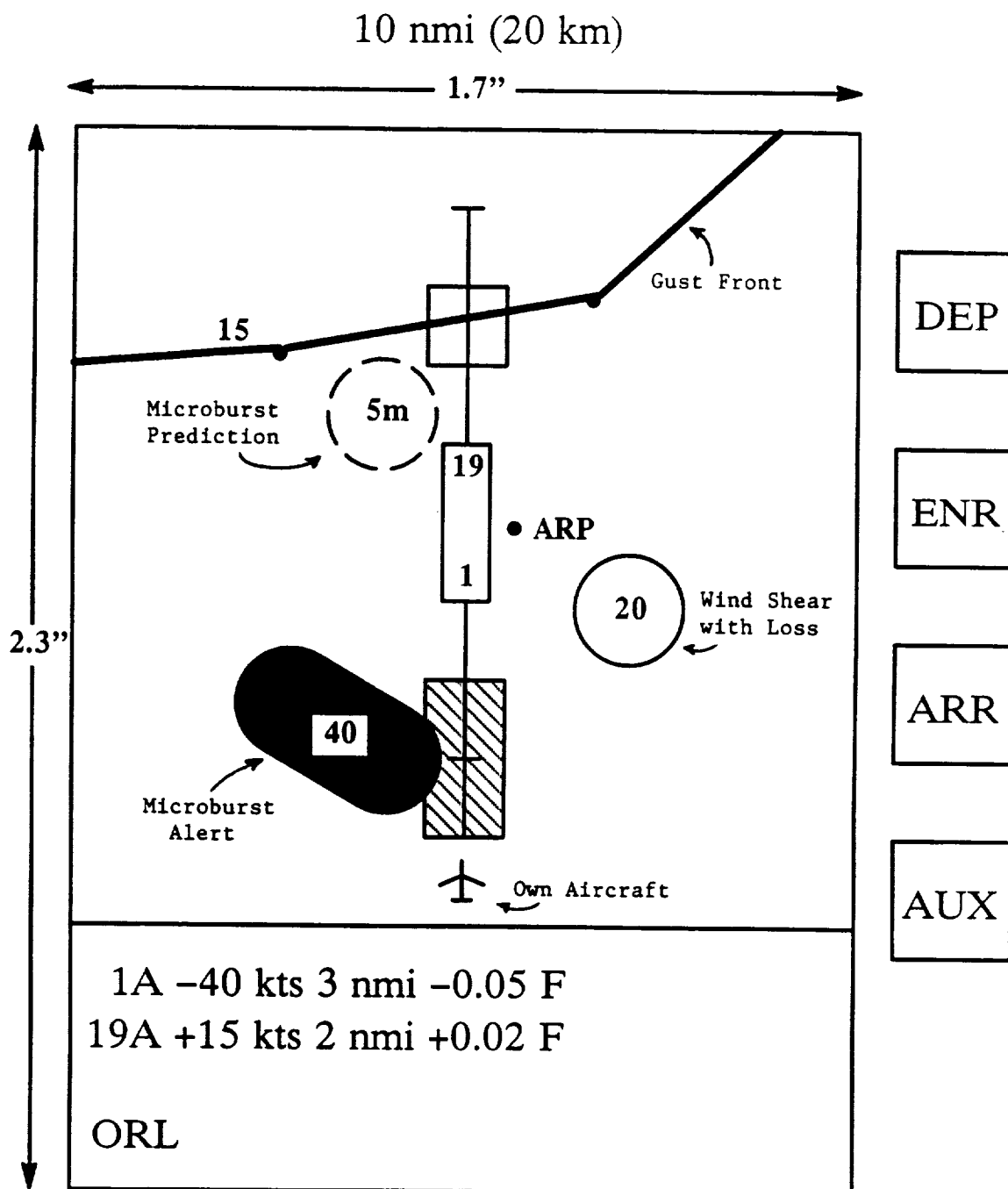
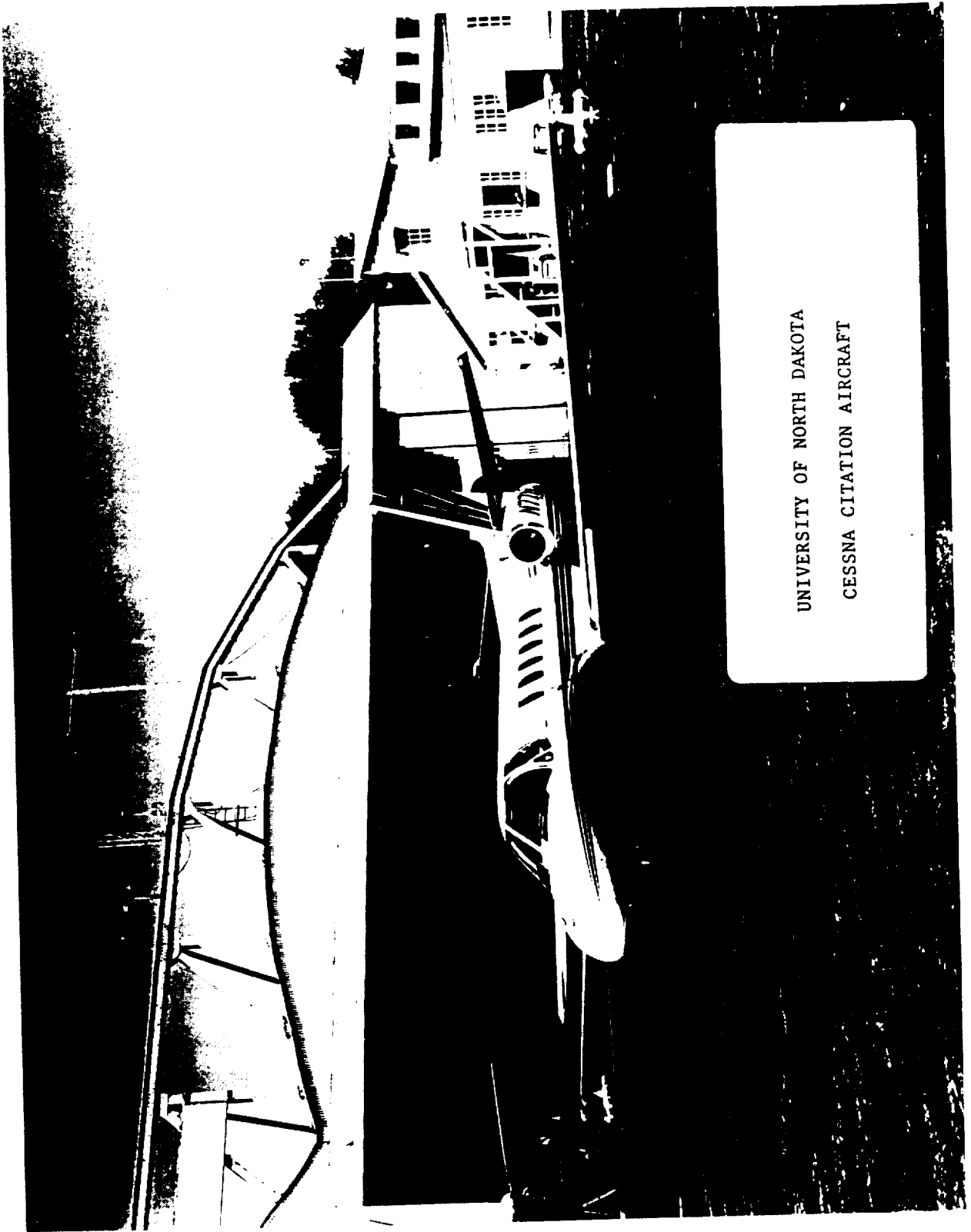


Figure 1. Cockpit wind shear display layout
(Arrival mode)

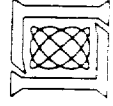


UNIVERSITY OF NORTH DAKOTA
CESSNA CITATION AIRCRAFT

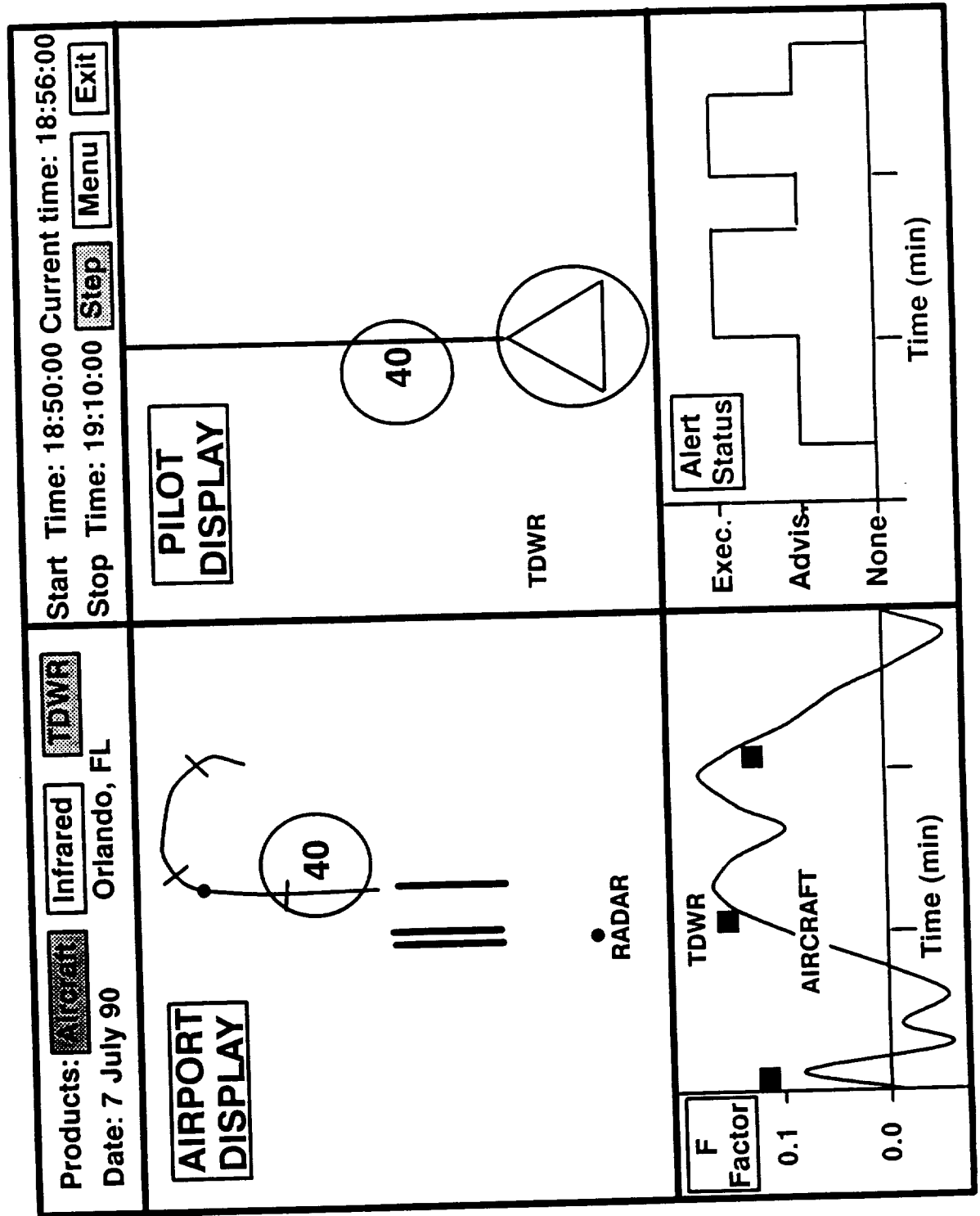
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FLIGHT OPERATIONS

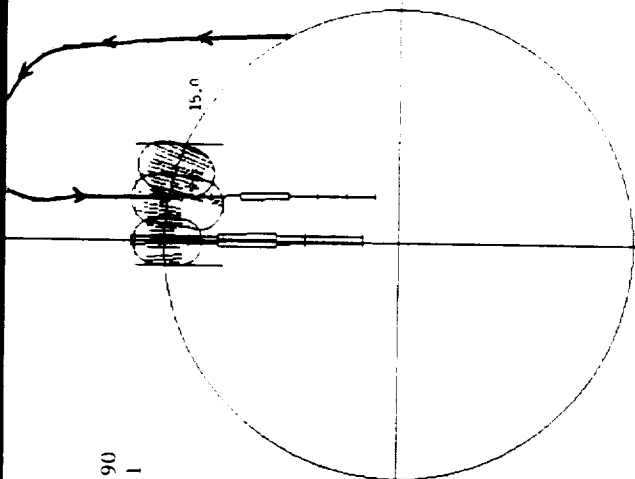
- **24 FLIGHTS (JUNE--JULY, SEP) BY UND AIRCRAFT**
- **64 MICROBURST PENETRATIONS (W/ RADAR COVERAGE)**
- **DATA GATHERED:**
 - CITATION AIRCRAFT DATA
 - INFRARED SYSTEM DATA (TPS)
 - TESTBED RADAR DATA AND ALGORITHM RESULTS
- **ANALYSIS SOFTWARE IN PROGRESS**



ANALYSIS WORKSTATION



7 JULY 90
PASS #1



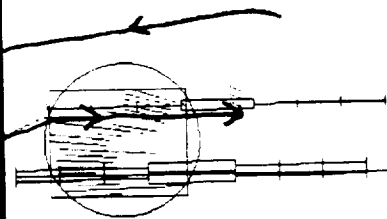
TDWR

Aircraft

7 JULY 90

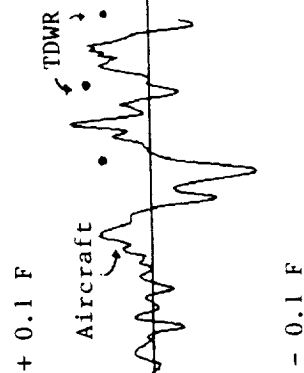
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7 JULY 90
PASS #3



07/07/90 19:10:36
07/07/90 19:10:37
07/07/90 19:10:38
Ast refresh mode: 1
07/07/90 19:10:39

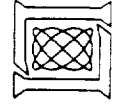
MB Tilt: 7 Jul 90 19:10:50
Site: Orlando
Elevation: 0.4000
MB shape
MB alarm
MB segments
MB Segment: 1
MB Level: 1
Citation:



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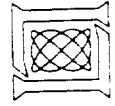
FY '90 ACCOMPLISHMENTS

- **COCKPIT DISPLAY OF TDWR WIND SHEAR PRODUCTS**
- **AIRCRAFT PENETRATIONS OF MICROBURSTS**
- **ANALYSIS SOFTWARE DEVELOPMENT**



FY '91 PLANS

- **ORLANDO '91 OPERATIONS**
- **F FACTOR ANALYSIS FOR CITATION FLIGHTS**
- **CREW WARNING PROCEDURE IMPLEMENTATION**
- **NASA 737 AIRCRAFT SUPPORT**



Orlando Experiment - Questions and Answers

Q: ED LOCKE (Thermo Electron Technologies) - What is the cost per airport of the TDWR as projected by Raetheon? How effective is the TDWR in seeing dry microbursts?

A: STEVE CAMPBELL (MIT Lincoln Laboratory) - I don't have the exact numbers here but I believe the total cost per airport is something on the order of 6 to 7 million dollars. On the other question; our feeling is that the TDWR is very effective in detecting dry microbursts. About the lowest reflectivity you're going to see in an outflow, even in Denver, is down in the order of -20 to -10 dBZ. That is well within the sensitivity rating of the TDWR. For the ASR9 with the wind shear processing you do have a sensitivity problem in a Denver type environment.

Q: NORMAN CRABILL (Aero Space Consultants) - Have you considered uplinking the microburst velocity divided by distance or the Bowles' F-factor to the pilot?

A: STEVE CAMPBELL (MIT Lincoln Laboratory) - We in fact did transmit that to the airplane but we didn't display it. We could have and perhaps should have. It was an operational decision.

Q: ED LOCKE (Thermo Electron Technologies) - Can you give the characteristics of the TDWR used in the tests at Orlando?

A: STEVE CAMPBELL (MIT Lincoln Laboratory) - I'll give you the characteristics for the TDWR as I recall them and our test bed is very similar to these characteristics. The wave length is 5 cm; the antenna diameter is 27 feet; the PRF is adaptive. We have an adaptive scheme where we scan at a low PRF of about 350 Htz. That allows us to identify unambiguously the very long range echoes. We then adaptively select a PRF which minimizes second trip folding into the first trip. In particular we try to minimize the folding around the immediate airport region. If there is folding that we can detect it, since we know unambiguously where all the range echoes are, we can determine from a given PRF where all the folding is occurring and flag the obscured cells. As a practical matter our PRF goes from something on the order of 700 Htz up to about 1200 Htz. The pulse energy of the Raetheon TDWR is a quarter of a gigawatt and the pulse length is one microsecond. Our pulse length make be a little bit shorter for technical reasons. The microburst alarms are updated once a minute. Our beam width, both horizontal and vertical is a half degree, actually TDWR is 0.55 degrees.

Session V. TDWR Data Link / Display

N91-24178

Integration of the TDWR and LLWAS Wind Shear Detection System
Larry Cornman, National Center for Atmospheric Research

Integration of the TDWR and LLWAS Wind Shear Detection Systems

by

Larry Cornman
National Center for Atmospheric Research*
Research Applications Program

Abstract

Operational demonstrations of a prototype TDWR/LLWAS integrated wind shear detection system were conducted at Denver's Stapleton International Airport during the 1989 and 1990 summer seasons. The integration of wind shear detection systems is needed to provide end-users with a single, consensus source of information. A properly implemented integrated system provides wind shear warnings of a higher quality than stand-alone LLWAS or TDWR systems.

The algorithmic concepts used to generate the TDWR/LLWAS integrated products and several case studies will be discussed, indicating the viability and potential of integrated wind shear detection systems. Implications for integrating ground and airborne wind shear detection systems will be briefly examined.

* NCAR is sponsored by the National Science Foundation.

**INTEGRATION OF
THE TDWR AND LLWAS
WIND SHEAR DETECTION SYSTEMS**

by

**Larry B. Cornman
National Center for Atmospheric Research
Research Applications Program**

OUTLINE

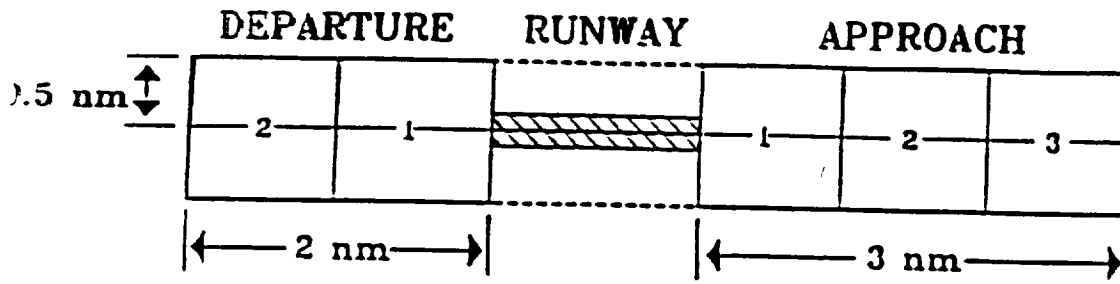
- **TDWR and LLWAS as Stand-Alone Systems**
- **Motivation for Integration**
- **Integration Concepts**
- **TDWR/LLWAS Integration Algorithm**
- **Connection to Airborne Wind Shear Systems**

WIND SHEAR COMPONENTS OF CURRENT TDWR AND LLWAS (STAND-ALONE) SYSTEMS

TDWR

- 0 Microburst Detection
 - (One-minute update rate)
 - Event region enclosed in "band aid" shape.Alerts generated when shape intersects runway corridor
- 0 Gust Front Detection
 - (5-minute update rate)
 - Event described by solid curve. Alerts generated when curve intersects runway corridor.
- 0 Displays
 - Alphanumeric: runway-specific alerts
 - Graphic: runway-specific alerts and event depiction

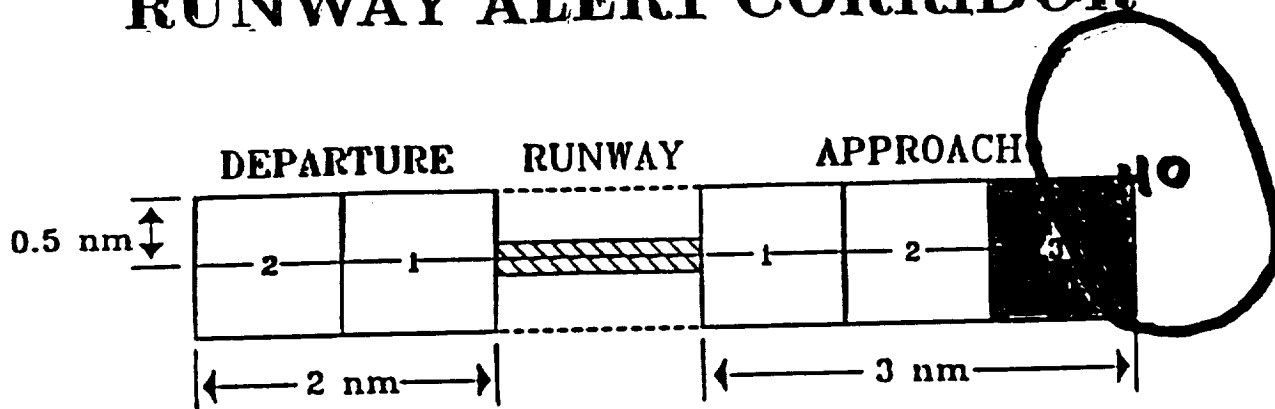
RUNWAY ALERT CORRIDOR



WIND SHEAR WARNING MESSAGE FORMAT

TYPE	WIND SPEED CHANGE	LOCATION
Wind Shear Microburst	Loss/Gain Knots	<div>1 mi</div> <div>2 mi</div> <div>3 mi</div> Approach
		<div>1 mi</div> <div>2 mi</div> Departure
		<div></div> <div></div> Runway

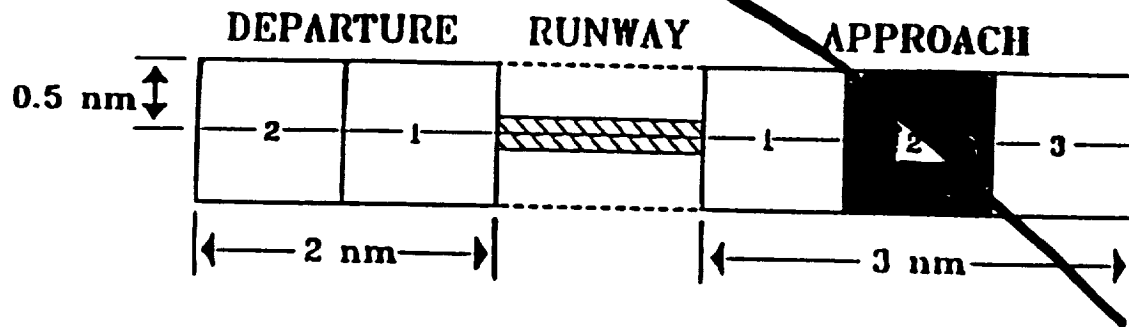
RUNWAY ALERT CORRIDOR



MICROBURST "BAND-AID" SHAPE

**IMPACTING RUNWAY
ALERT CORRIDOR**

RUNWAY ALERT CORRIDOR



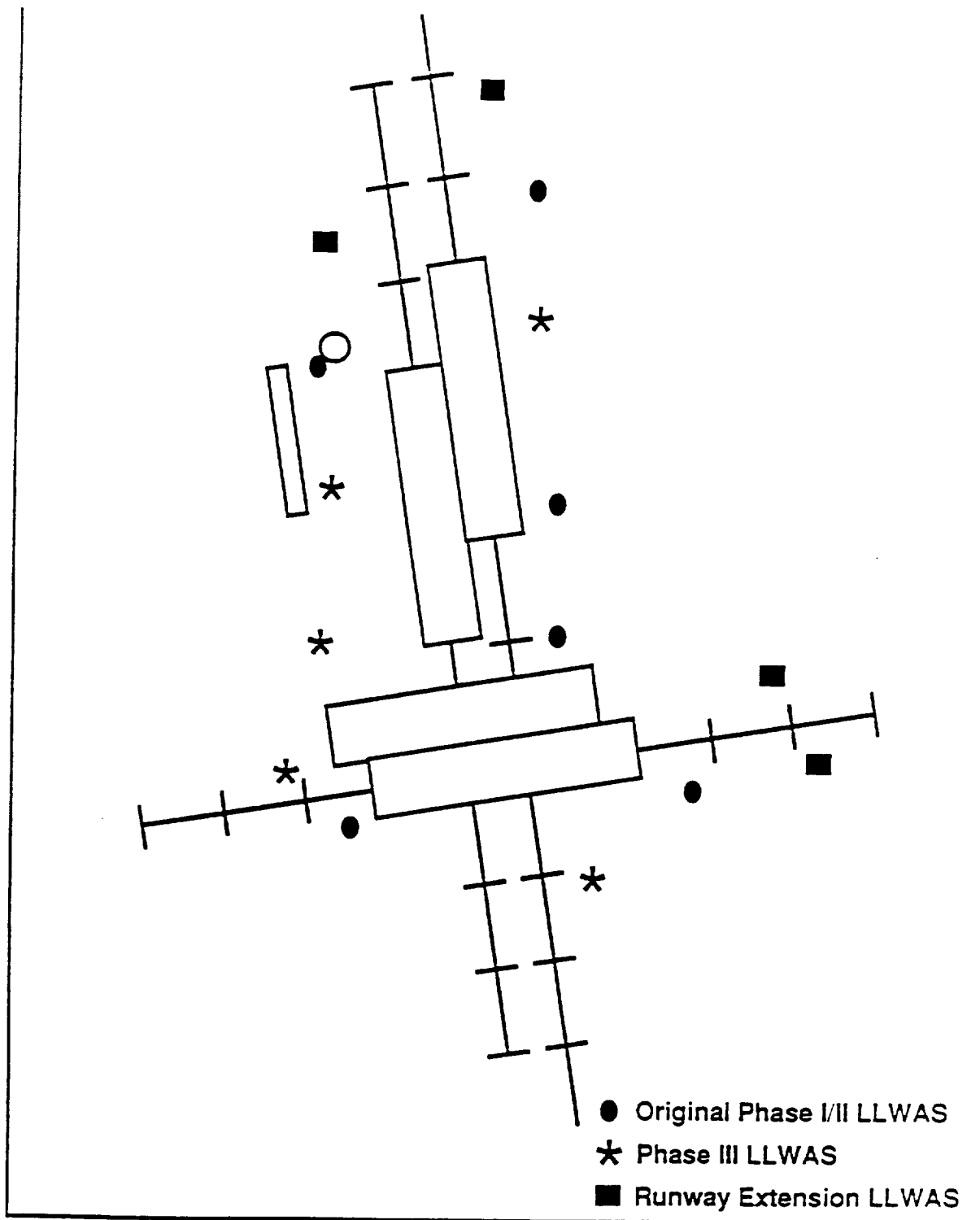
TDWR GUST FRONT CURVE IMPACTING RUNWAY ALERT CORRIDOR.

WIND SHEAR COMPONENTS OF
CURRENT TDWR AND LLWAS (STAND-ALONE) SYSTEMS
(continued)

LLWAS

- 0 Phase I: Original "six station".
- 0 Phase II: "Six station", algorithm upgrade.
- 0 Phase III: "Network expansion". Additional stations, further algorithm upgrades: microburst detection, runway-specific alerts.
- 0 Runway extension: "3-mile extensions". Additional stations to protect full runway corridor.

LLWAS ANEMOMETER NETWORK STAPLETON INT'L AIRPORT



WIND SHEAR COMPONENTS OF
CURRENT TDWR AND LLWAS (STAND-ALONE) SYSTEMS
(continued)

LLWAS (continued)

- 0 Phase III/Runway Extension:
 - Microburst detection
 - Runway-oriented loss and gain detection
 - (10-second update rate)
 - Displays
 - Alphanumeric: runway-specific alerts,
(identical format as for TDWR)
- 0 Integration "Add-On":
 - microburst region enclosed in "band aid" shape
(identical to TDWR)

MOTIVATION FOR INTEGRATION

- 0 Both stand-alone systems do a good overall job detecting wind shear:
 - TDWR and LLWAS have very good microburst probability of detection (POD >90%) and low false alarm rates (FAR <10%).
 - Gust front detection and false alarm values are not quite as good, yet acceptable.
- 0 SO, WHY DO WE NEED TO INTEGRATE?
 - These numbers don't tell the whole story ...

MOTIVATION FOR INTEGRATION

(continued)

- 0 Cannot have two separate display systems:
 - * Physical Space for Displays in ATCT
 - * Two, (Potentially Different), Sets of Wind Shear Information
 - * Users (pilots, air traffic controllers) should not have to interpret wind shear information based on a variety of sources.

- 0 Provides Back-Up Capability
 - * Each system can continue to operate independently.

MOTIVATION FOR INTEGRATION (continued)

- 0 The Probability of Detection and False Alarm Rates for Integration Will be Better than Those for the Stand-Alone Systems.
 - Since the stand-alone statistics are already quite good, the integration benefits might appear to be only marginal.
- 0 These Numbers Don't Really Reflect the Key "Value-Added" Components of Integration ...

MOTIVATION FOR INTEGRATION

(continued)

Integration "Value-Added Factors:

1. Increased Timeliness

- TDWR can detect events moving into airport area.
- TDWR can detect microbursts impacting between LLWAS anemometers before the outflow reaches them.
- TDWR has predictive capabilities.

MOTIVATION FOR INTEGRATION (continued)

- LLWAS has a faster update rate than TDWR (surface scans): 10 sec. vs. 60 sec.
- So, for rapidly changing events, LLWAS can "monitor" the situation better:
 - o first detection
 - o increasing/decreasing magnitude
 - o event location and size
 - o event cessation

MOTIVATION FOR INTEGRATION (continued)

2. Integration Covers "Partial Misses" (Spatial)

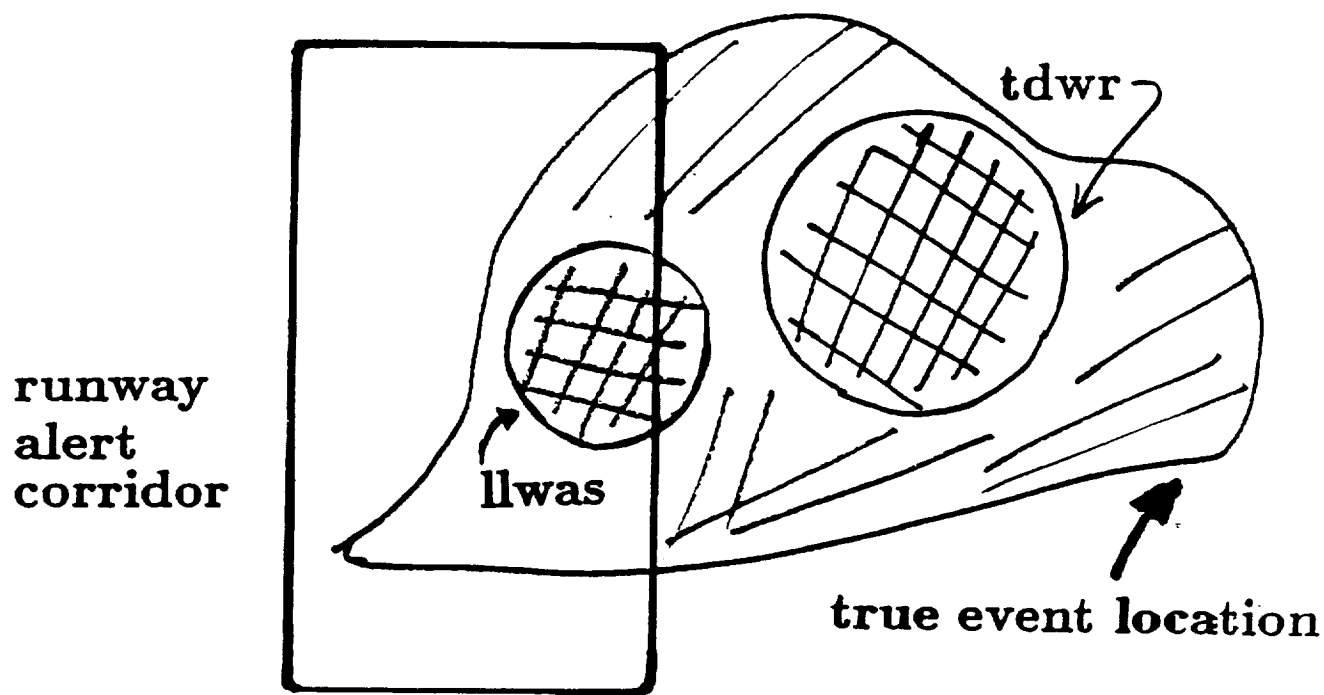
0 Detection statistics are based on seeing "most" of the event.

*However, pilots need to know what is impacting their specific flight path!

0 TDWR can detect events (or portions thereof) impacting runway corridor, yet outside LLWAS network.

0 LLWAS can "cover" for TDWR in cases of asymmetry and low-reflectivity.

COVERING "PARTIAL MISSES"



CORRECT DETECTION ??

MISSED DETECTION ??

***** BOTTOM LINE *****

CORRECT RUNWAY ALERT

MOTIVATION FOR INTEGRATION (continued)

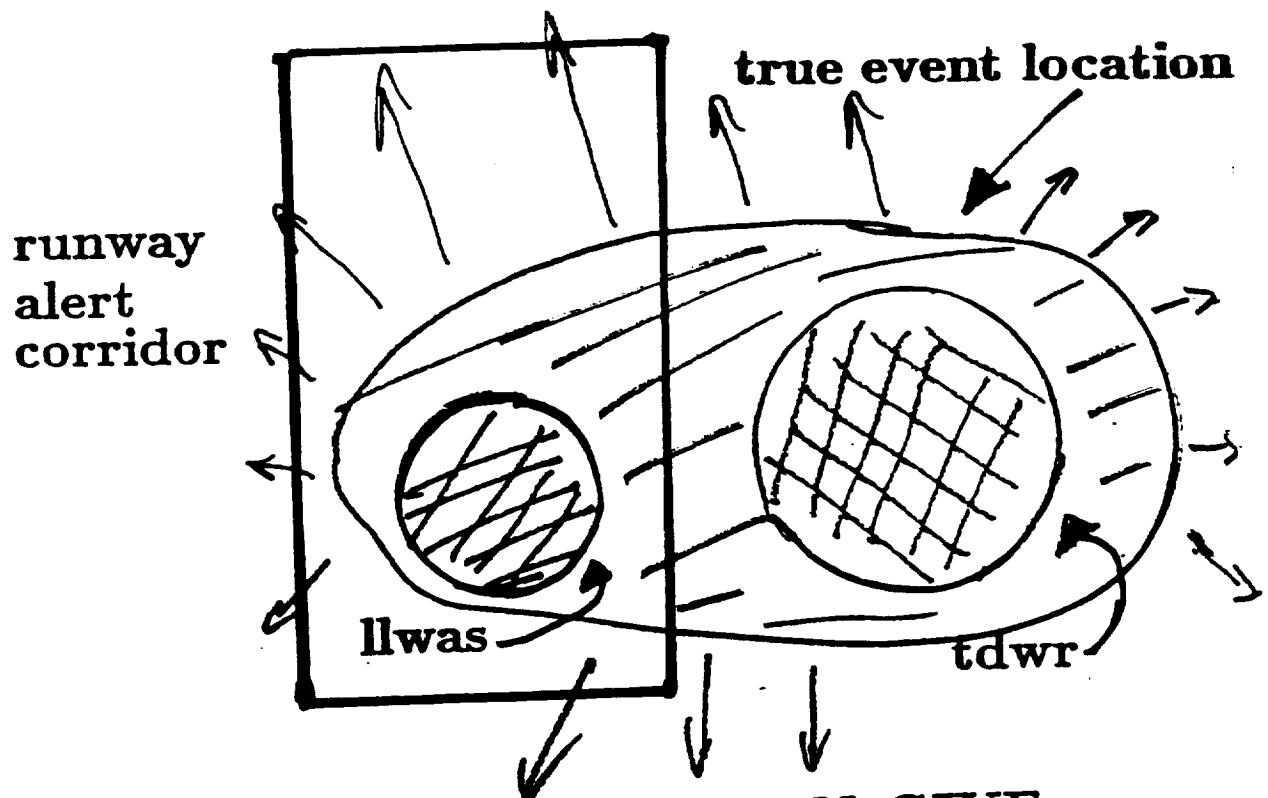
3. Runway Component Estimates

- 0 Again, pilots need to know what to expect along their flight path.
- 0 However, TDWR and LLWAS make assumptions as to what the runway shear truly is . . .

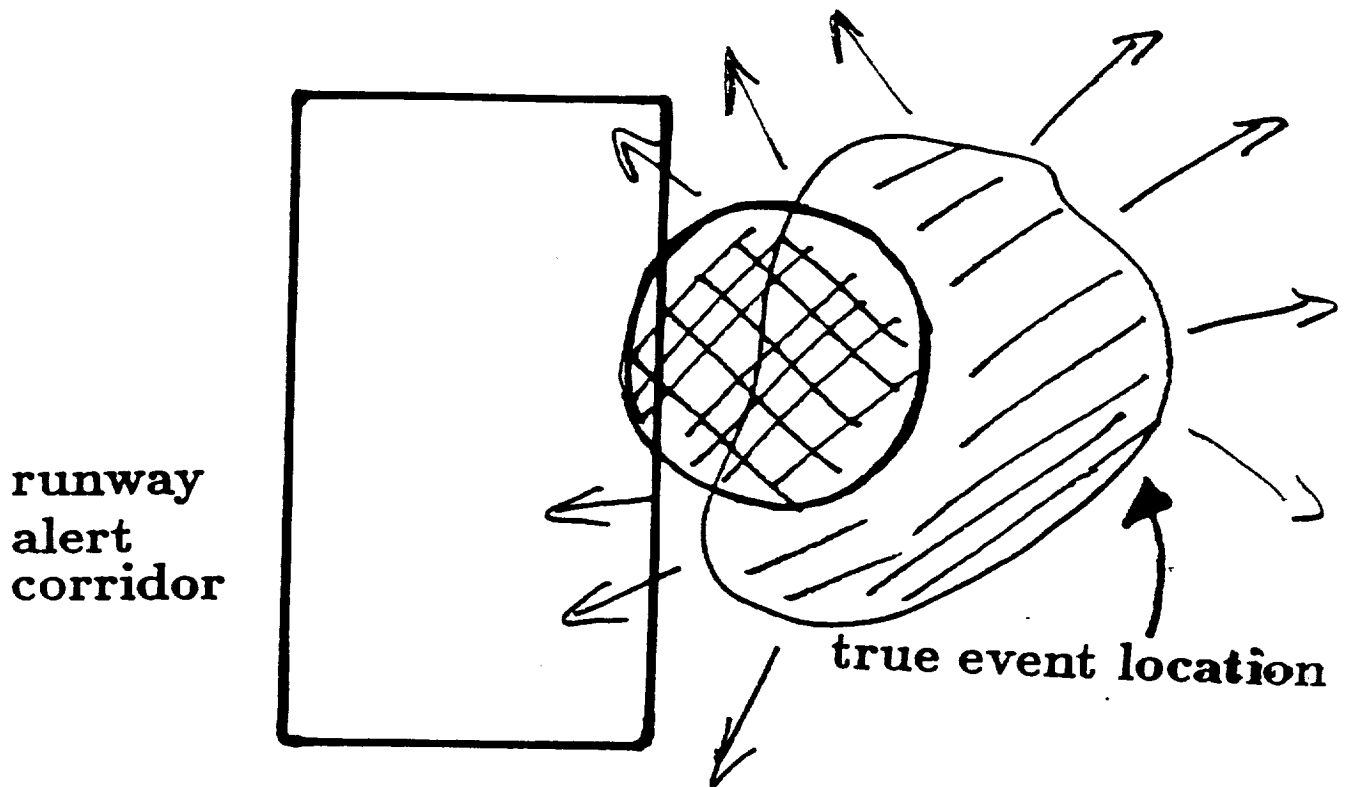
MOTIVATION FOR INTEGRATION (continued)

- 0 Problems for TDWR can arise in cases of asymmetry, low-reflectivity, rapidly changing event magnitude, and "grazing impact" to runway corridor.

EVENT ASYMMETRY



“GRAZING IMPACT”



**VIA INTEGRATION,
ONE SYSTEM COULD BE USED
TO “VALIDATE” THE OTHER**

MOTIVATION FOR INTEGRATION

(continued)

0 Problems for LLWAS include: undersampling of wind due to low spatial resolution, underestimates caused by sheltering and/or lack of vertical resolution, and overestimates due to noisy winds.

****However, both systems compliment each other quite well: the strengths of one can often negate the weaknesses of the other.**

MOTIVATION FOR INTEGRATION (continued)

Other Factors:

- 0 Winter vs. Summer
 - Hazardous wind shear conditions can occur in non-convective weather. TDWR may be unable to detect these events due to lack of reflectors, while LLWAS can.
- 0 Detection of strong convergence in microburst outflow region. LLWAS can detect these (often very hazardous) situations.

OVERVIEW OF GENERIC INTEGRATION CONCEPTS

- 0 Exploit Strengths of Stand-Alone Systems**
- 0 Limit Impact of Weaknesses of Stand-Alone Systems**
- 0 User-End Products (Graphic and Alphanumeric) Should Be Transparent as to Source**

OVERVIEW OF GENERIC INTEGRATION CONCEPTS (continued)

Three Possible Techniques:

1. Alphanumeric-Level
 - o Generate consensus of runway alerts by taking "worst case" alphanumeric alerts from stand-alones.
2. Data-Level, "Bottom-Up"
 - o Synthesize raw data to then generate end-products.
3. Product-Level, "Top-Down"
 - o Utilize intermediate products to generate end-products. "Expert-system".

Description of TDWR/LLWAS Integration Algorithm

- 0 Product-level Technique
- 0 Two basic windshear warning components
 - * Windshear-with-loss (MB's, etc)
 - * Windshear-with-gain (G.F.'s, etc)
- 0 Generates graphical and alphanumeric displays

Description of TDWR/LLWAS Integration Algorithm (continued)

0 Wind Shear-with-Loss:

- * Implemented Technique for Generating Microburst Shapes from LLWAS
- * To eliminate LLWAS false alarms, a technique for "validating" weaker (15-20 kt) LLWAS microburst detections was implemented using additional meteorological information available from the TDWR system.
- * "Union" of TDWR and "Validated" LLWAS Microburst Shapes

C-F

Description of TDWR/LLWAS Integration Algorithm (continued)

0 Wind Shear-with-Gain:

- * LLWAS runway-oriented-gain computations used within LLWAS network
- * TDWR gust front used outside LLWAS network

Description of TDWR/LLWAS Integration Algorithm (continued)

FUTURE (?):

- 0 Use LLWAS information to address TDWR microburst (spatial and temporal) "overwarning" problem.
- 0 Modifications to wind shear-with-gain technique with advanced TDWR gust front algorithm.

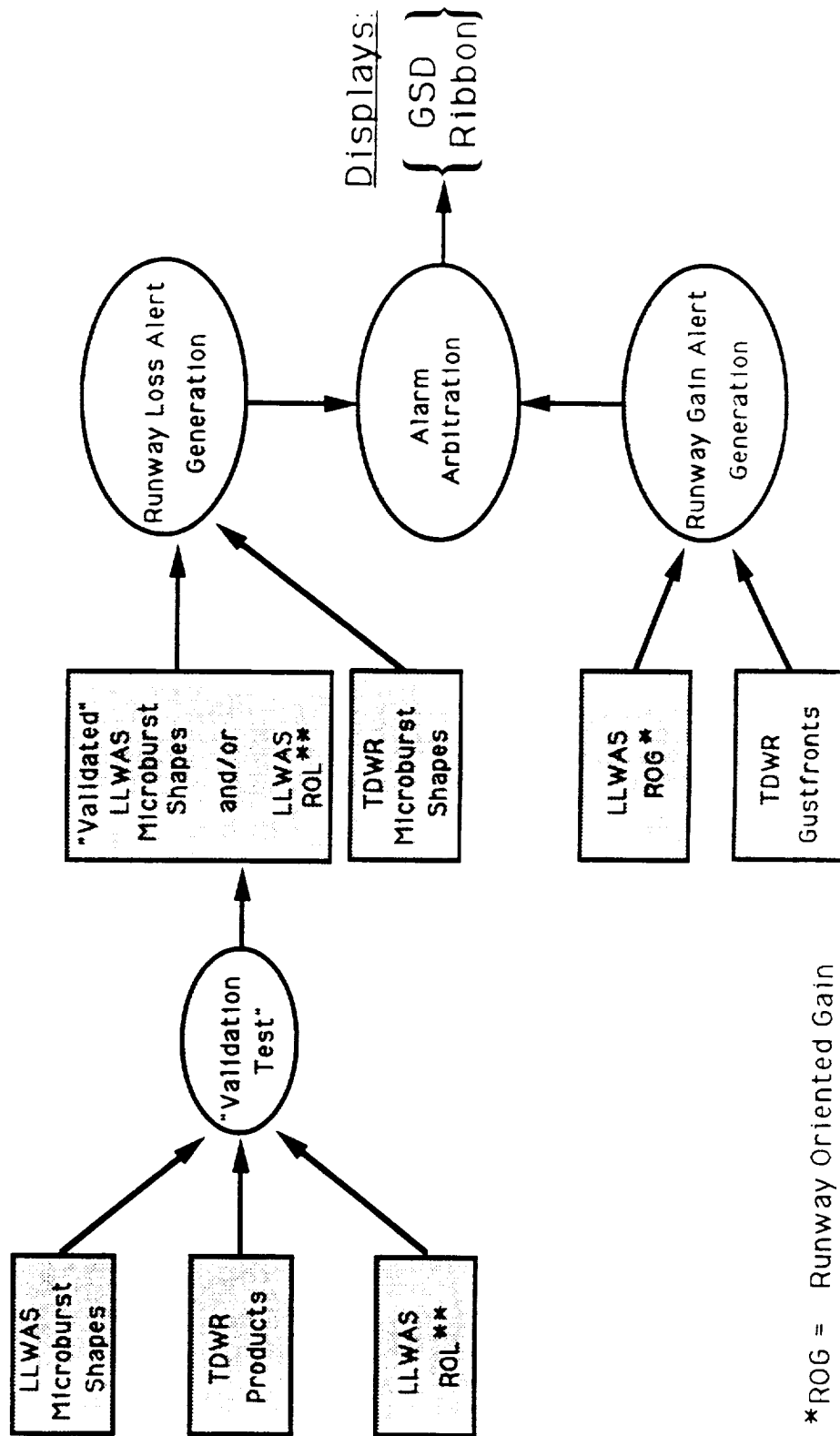
COMPARISON AND CONTRAST OF TDWR AND LLWAS DATA & PRODUCTS

Category	TDWR	LLWAS
* Spacial Resolution	High	Low
* Temporal Resolution	Low	High
* Velocity Data Measurements	Radial2-D	
* Reflectivity Information	Yes	No
* Above-Surface Information	Yes	No
* Areal Coverage	Large	Small
* Potential for Microburst Prediction	Yes	No

INTEGRATION ALGORITHM STRUCTURE

FULL SYSTEM

1990



*ROG = Runway Oriented Gain

**ROL = Runway Oriented Loss

Connection to Airborne Wind Shear Systems

- 0 Data link ground based alarms to aircraft.
- 0 Must integrate in some form.
- 0 "Product-level" integration scheme could be applied.
- 0 NCAR and NASA will begin working on this problem in 1991.

BOTTOM LINE

- 0 With more than one system, we must integrate.
- 0 Integration's "value-added" qualities are very important.
- 0 TDWR/LLWAS integration works very well based on 1989 and 1990 operational demonstrations.

Integration of the TDWR and LLWAS Wind Shear Detection System Questions and Answers

Q: WALT OVEREND (Delta Airlines) - Are LLWAS sensors located high enough, that is, out of ground effect, to be really sensing the relevant air mass or the prevailing air mass as it effects the runway?

A: LARRY CORNMAN (NCAR) - In a sense there are two parts to that question. One is the sheltering effects and the other is the accuracy of measurements that are that close to the ground relative to what a pilot would see along the glide slope. The first part of the question in terms of the accuracy of measurements from poor locations is something the FAA has dealt with and is part of some of the upgrades to the six stations, certainly the enhance LLWAS system. Sheltering effects are taken care of by either raising the sensors or moving them. The second part of the problem is very difficult. You can only raise the pole so high. The sensor close to the runway surface is probably a very good estimate of what the pilot would see. Out further from the runway, one, two, or three miles, it gets worse. Again, you're limited by the location and the size of the pole that the sensors are on.

Q: GREG HAEFFELE (Boeing) - If both systems alert on the same microburst, but at different intensities, which takes precedence? If detected by both systems, does the "bandaid" size increase to encompass both areas?

A: LARRY CORNMAN (NCAR) - Basically, it's independent. LLWAS and TDWR both produce bandaids independently. The technique for issuing an alert is based on the technique that was developed for TDWR, that is, a bandaid intersecting a runway gives a magnitude and location. If you add more shapes you add extent and potentially larger magnitude. The idea is to pick the largest magnitude in the first potential event encountered.

Q: PAUL ROBINSON (Lockheed) - Complaints from pilots on wind shear reporting have been largely due to too much information. For example, wind speed and direction at different points on the airfield. Is this information from the LLWAS? If not, what information is communicated from ATC to the pilot concerning wind shear on the approach from LLWAS? If so, can the information be compressed into a more manageable form?

A: LARRY CORNMAN (NCAR) - Basically, that's been done. In phase III the alerts are runway specific, and that was part of the TDWR / LLWAS user group work that went into simplifying that data and make it more precise so each runway would have a specific alert.

Q: HERB SCHLICKENMAIER (FAA) - In one of your charts, you showed the product-level integration tests in '90. In it, you used TDWR precipitation to validate LLWAS information. Could the ASR-9 precipitation product be introduced in lieu of the TDWR?

A: LARRY CORNMAN (NCAR) - The product level integration technique that I put together doesn't care what the source is. So, in fact, right now with the wind shear detection program going on with ASR-9 the product output from that system would look identical to the TDWR output. Not only could the precipitation product be used in a similar fashion but the detection of events with a bandaid in a sense would fall through.

Session V. TDWR Data Link / Display

A Status Report on the TDWR Efforts in the Denver Area
Wayne Sand, National Center for Atmospheric Research

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A Status Report on the TDWR Efforts in the Denver Area

by

**Wayne Sand
Research Applications Program
National Center for Atmospheric
Research**

for

**17 October 1990
NASA Langley Research Center
Third Combined Manufacturers and
Technologists Airborne Wind
Shear Review Meeting**

A Status Report on the TDWR Efforts in the Denver Area

by

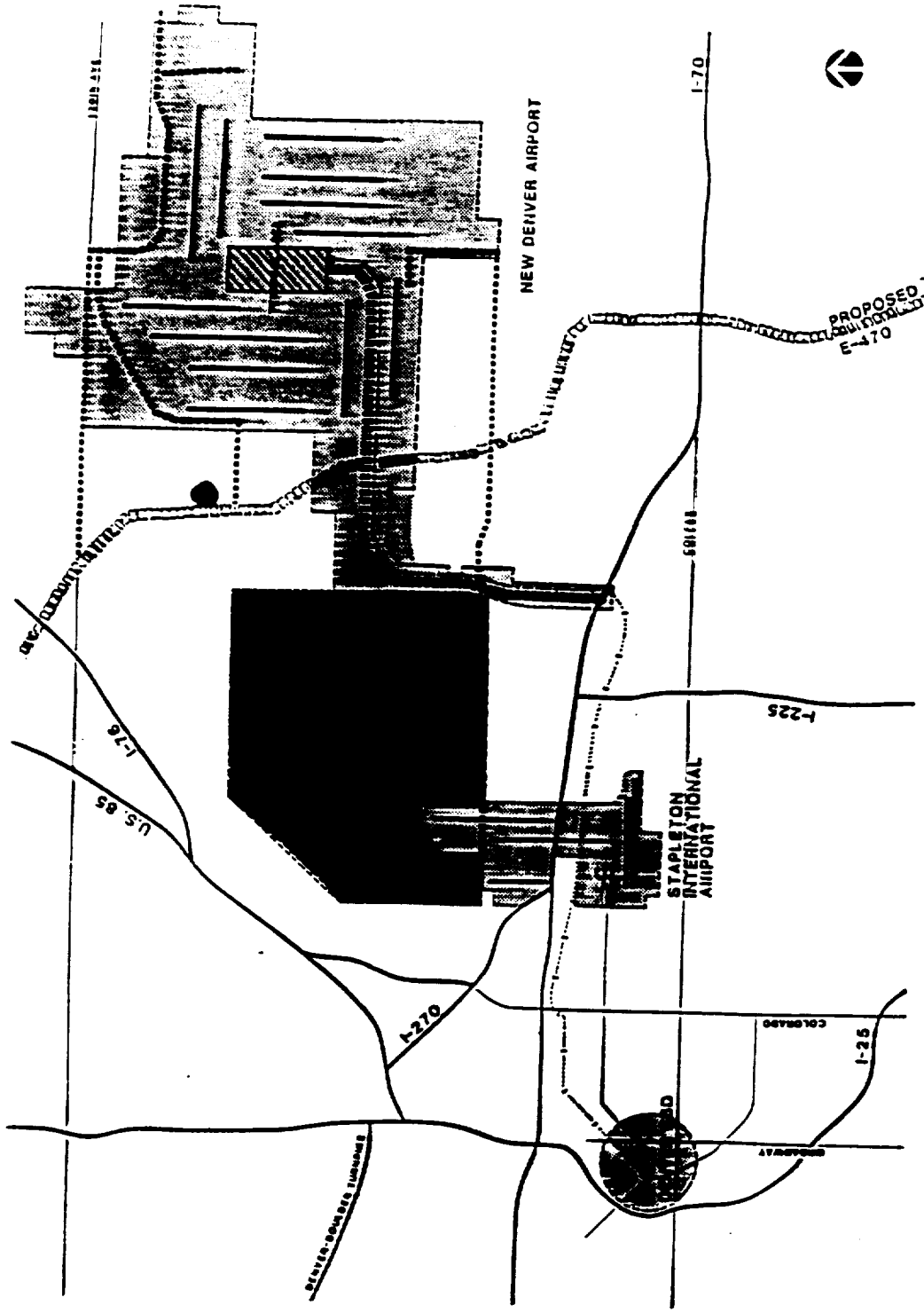
Wayne Sand

**National Center for Atmospheric Research*
Research Applications Program**

Abstract

A prototype radar developed by Raytheon as part of the NEXRAD program is currently being operated in Denver, Colorado, by the National Center for Atmospheric Research (NCAR). The Federal Aviation Administration has contracted NCAR to use output from the radar to duplicate the wind shear detection capability of a Terminal Doppler Weather Radar (TDWR) in an effort to continue development of TDWR algorithms and to protect Stapleton Airport. NCAR's efforts as they relate to the ground-based wind shear detection program will be summarized. The presentation will include a discussion relating in-flight microburst encounters to the severity of the events as detected by the TDWR system. Controllers' and pilots' perceptions of the system, overall detection and false alarm statistics from the system, and microburst alarm threshold logic will be discussed.

* NCAR is sponsored by the National Science Foundation

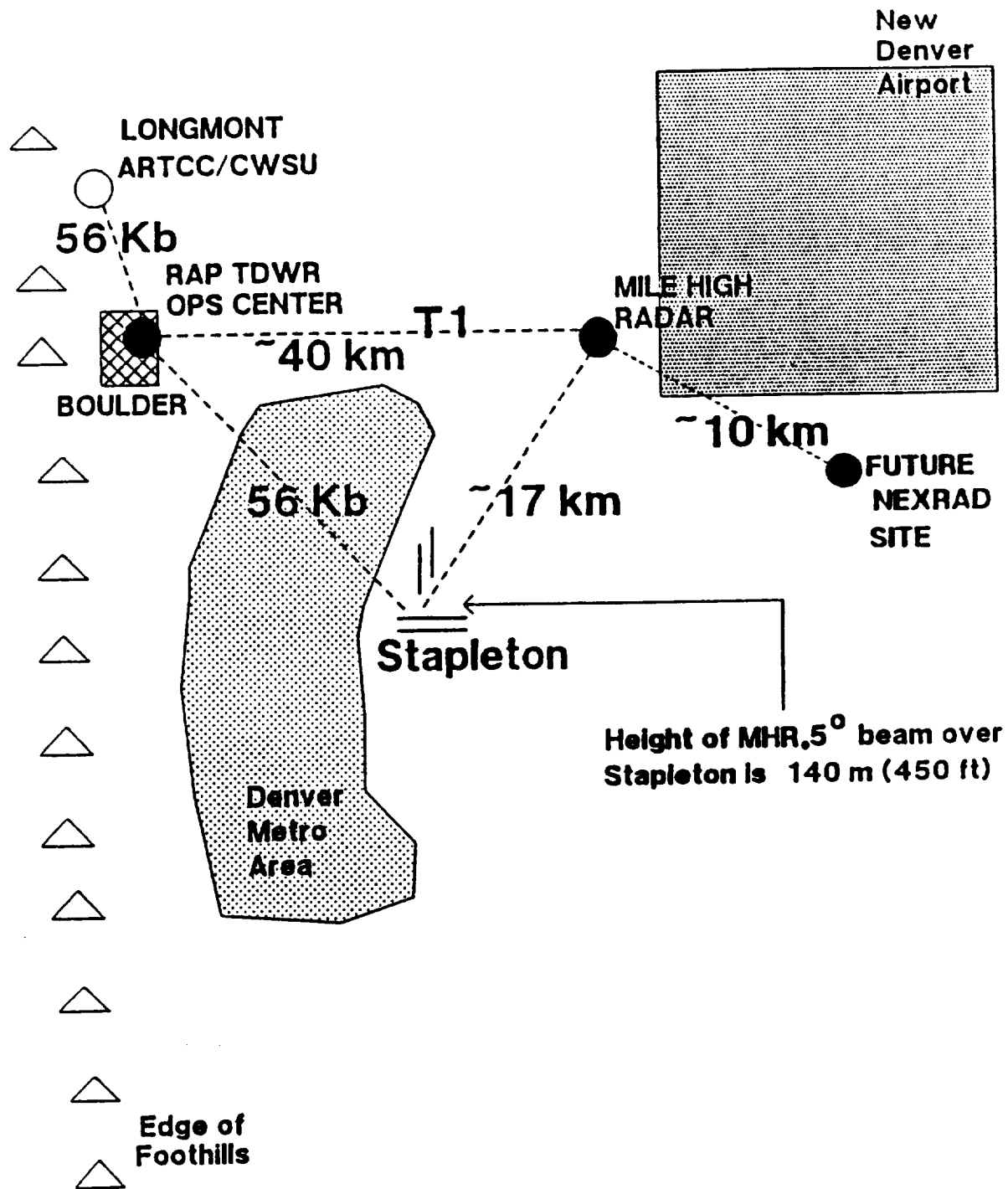


• MHR Site

PRELIMINARY

NEW DENVER AIRPORT VICINITY PLAN
JUNE 1988

Denver Terminal Doppler Weather Radar (TDWR) Geographical Setting



Project Summary

1990 Denver TDWR Program

Shakedown Period: 1-31 May

Operational Period: 1 June-7 Sept

Products Delivered:

- * TDWR/LLWAS Integrated Alarms**
- * Gust front Detection and Prediction**
- * LLWAS Operational Winds**
- * Precipitation (Reflectivity)**
- * Storm Motion**
- * Nowcast Product**

Operational Summary:

- * Hardware Problems**

**Two days down due to
Radar hardware failure,
other minor problems due
to hardware and software**

- * Weather events within 5 nm
of the Airport center**

- > Microburst**

95 Events (30-70 Kts)

17.6 Hours

**(50 affected the
airport)**

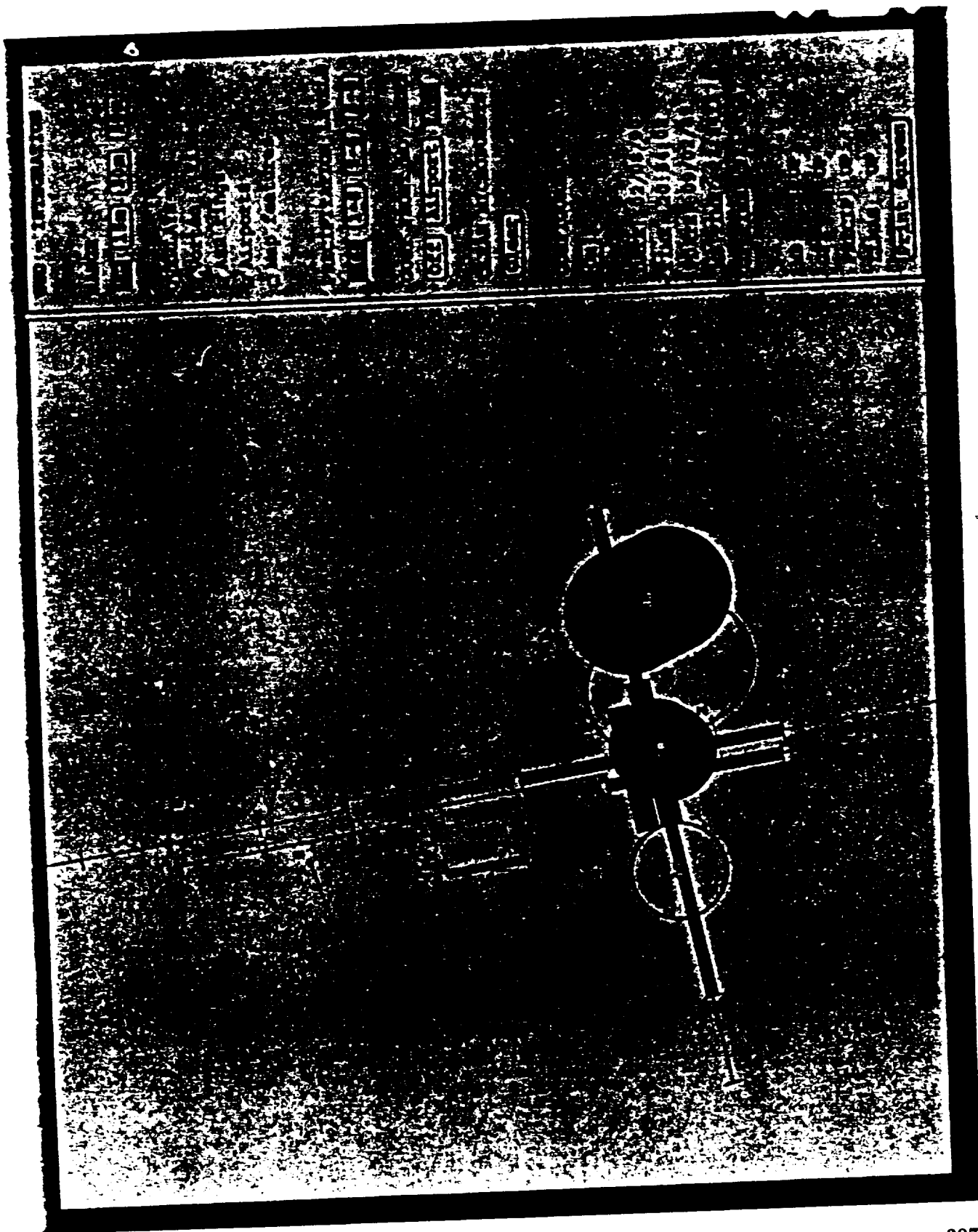
- > Wind shear with loss**

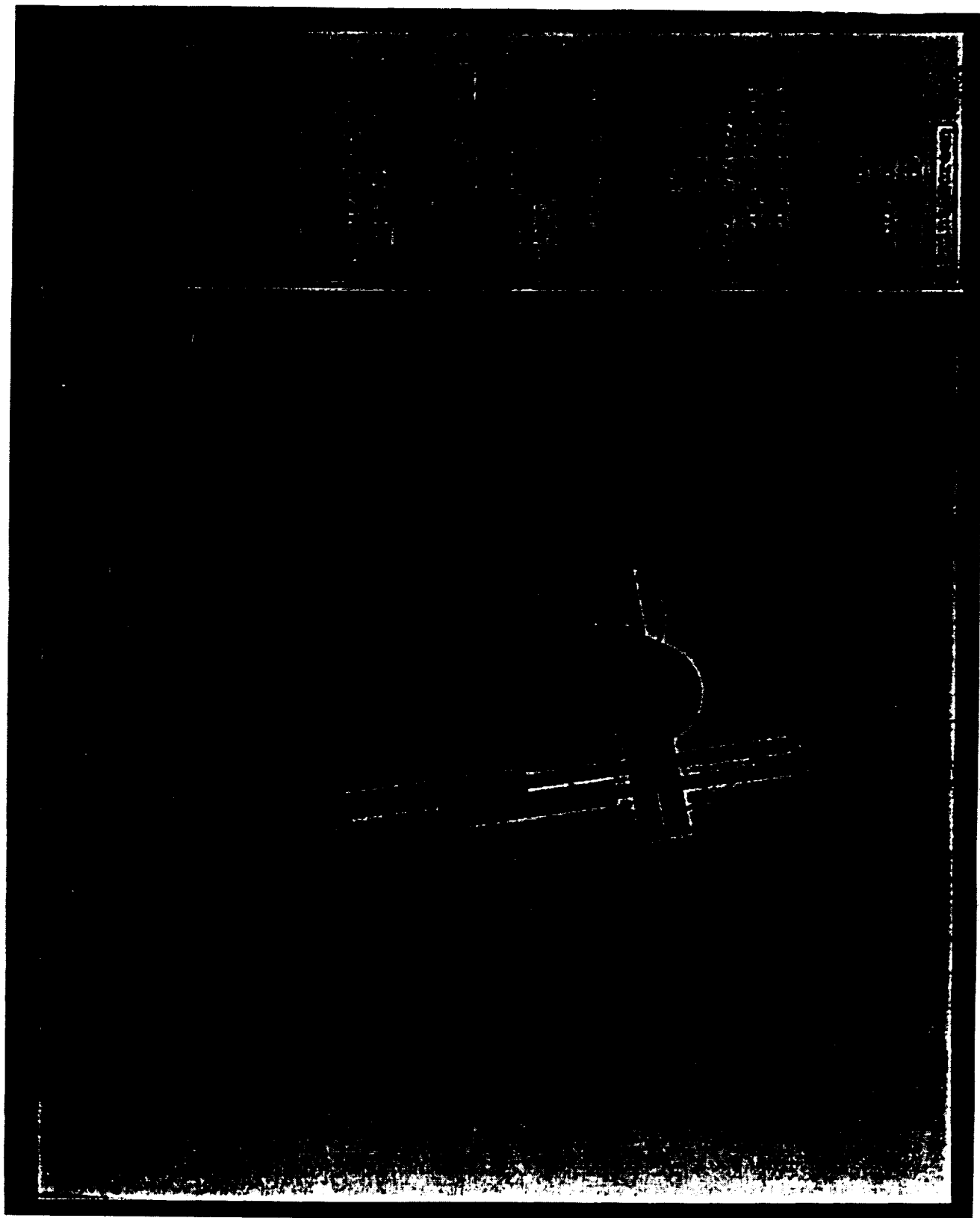
159 Events (15-30 kts)

- > Wind shear with gain**

65 Events (15-45 kts)

- * Performance of the system, quick look**
 - > Greater than 90% POD**
 - > Less than 5% FAR**





GSD - INTEGRATION

RANGE

5m 15m 30m 50m

Clear Microbursts

Overlays

Products

Configure Runways

NOWCAST: DOWN

DATE: 10/15/90

TIME: 14:48:14

PDATE: 07/01/90

MB TIME: 23:30:43

GF TIME: 23:30:43

MB: UP

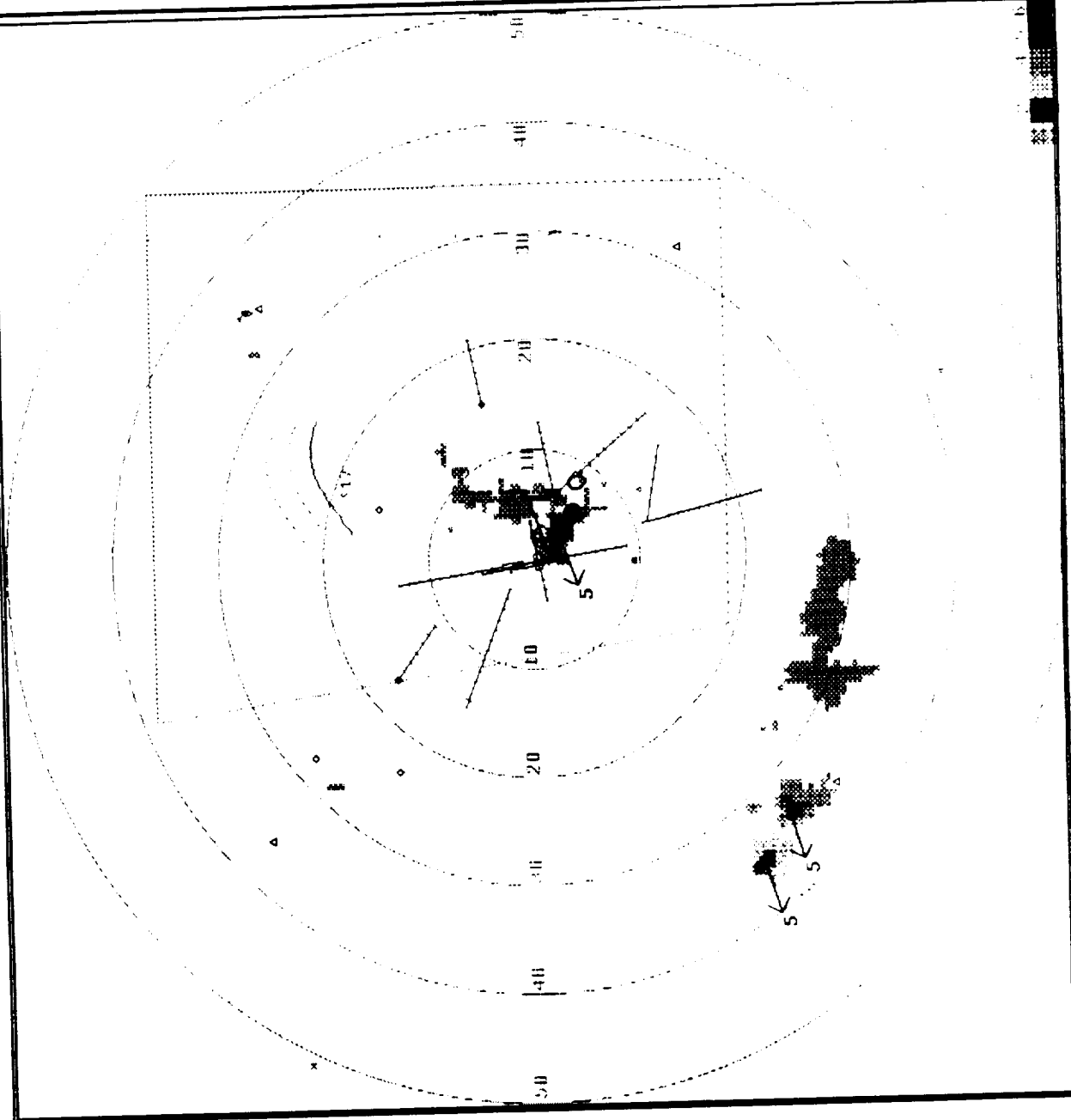
GF: UP

PRECIP: UP

LLWAS: UP

TAP: UP

Print Screen



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1990 OPERATIONAL DEMONSTRATIONS

USER INTERFACE ASPECTS

NOTIFICATION OF 1990 OPERATIONAL DEMONSTRATIONS

- PRESEASON AIRLINE BRIEFING
- LETTER TO AIRMEN
- NOTAMS
- PILOT QUESTIONNAIRES
- NOTIFICATION ON ATIS
- ATC TRAINING SESSIONS

PILOT REACTIONS

- FEWER OPERATIONS DURING MBAs; HOWEVER SOME STILL OCCUR
- FEWER TAKEOFFS WITH 15 KT LOSS ALERTS

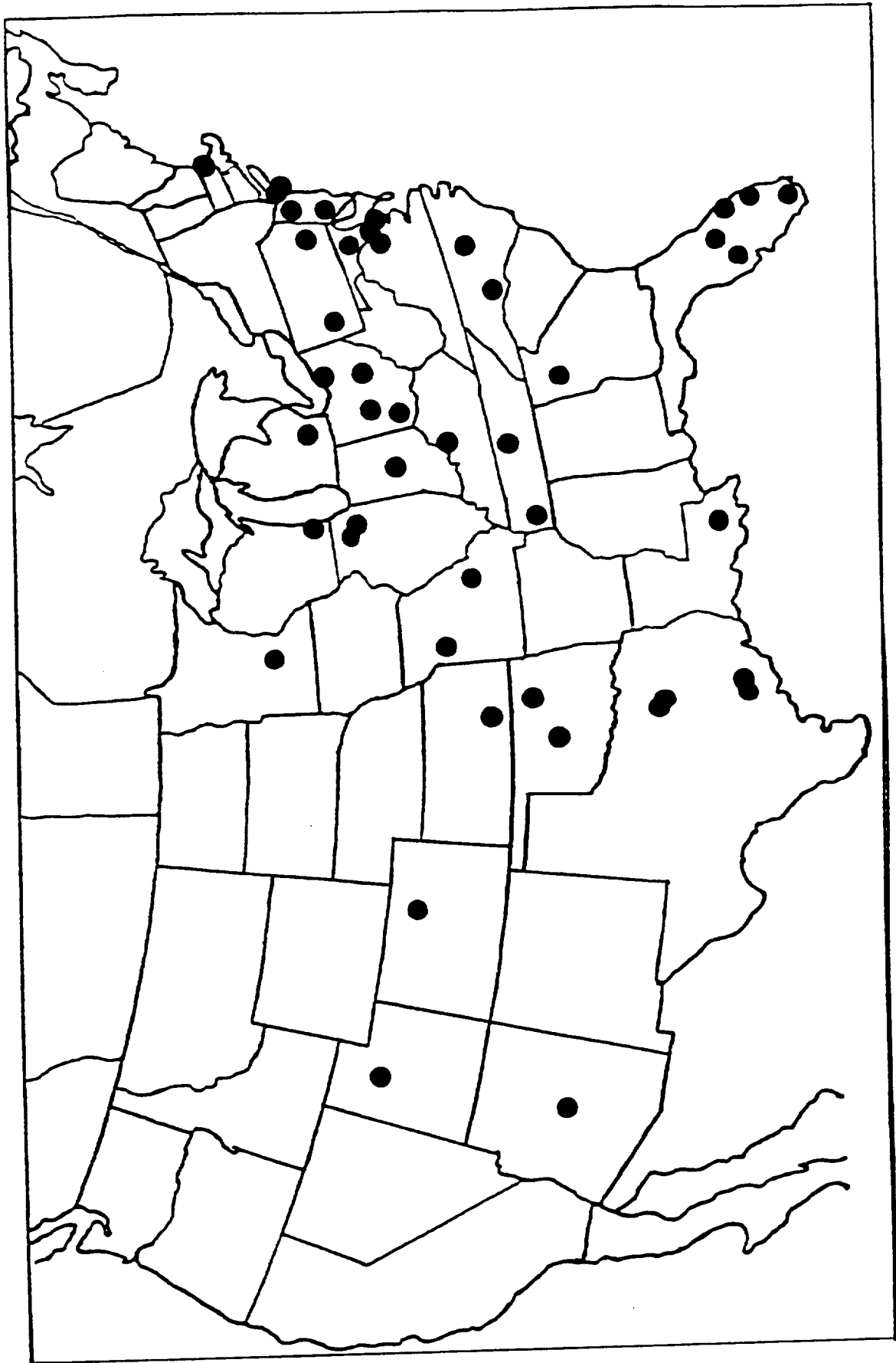
PILOT QUESTIONNAIRES

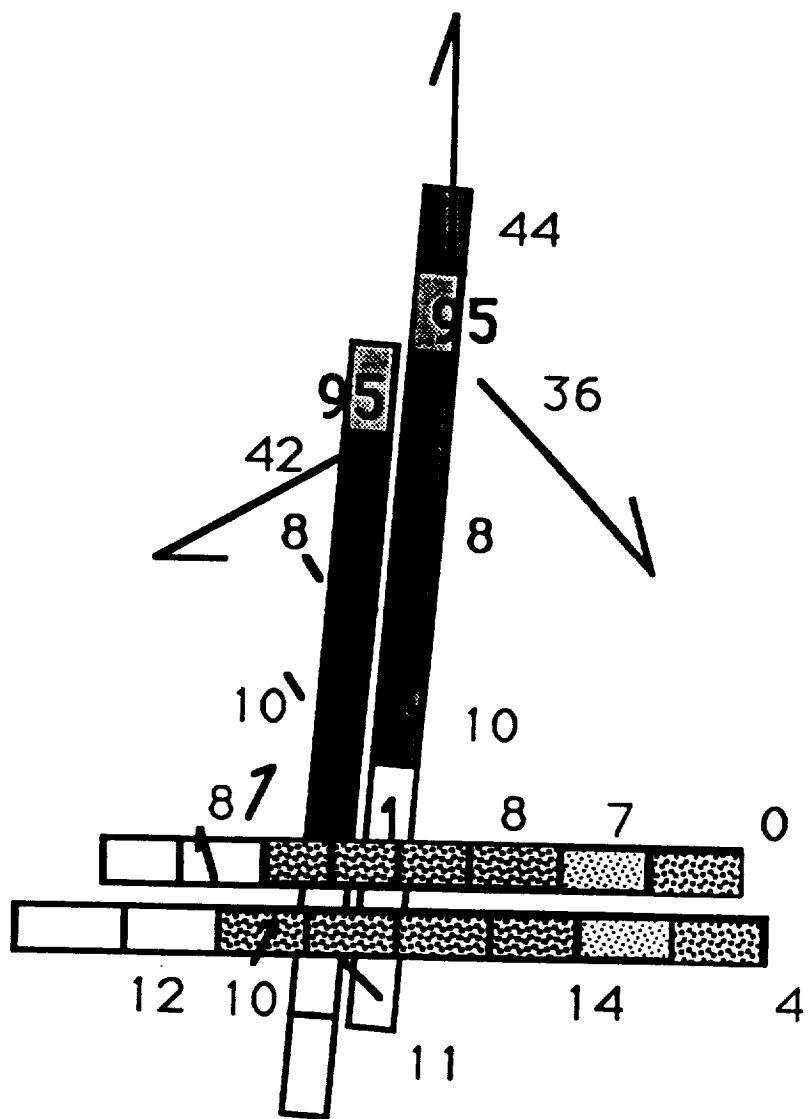
- PROVIDES PILOTS A MEANS TO COMMENT ON SYSTEM
- VERY SMALL PERCENTAGE RESPONSE
- PILOTS REPORT "SIGNIFICANT" WIND SHEAR ENCOUNTERS BEGINNING AT 10 KTS

ANALYSIS EFFORTS TO REDUCE "NUISANCE" ALARMS

- 15 KT ALARMS
- MODIFICATIONS TO WIND SHEAR WARNING BOXES
- REDUCTION IN SIZE OF MB SHAPES

TDWR Sites





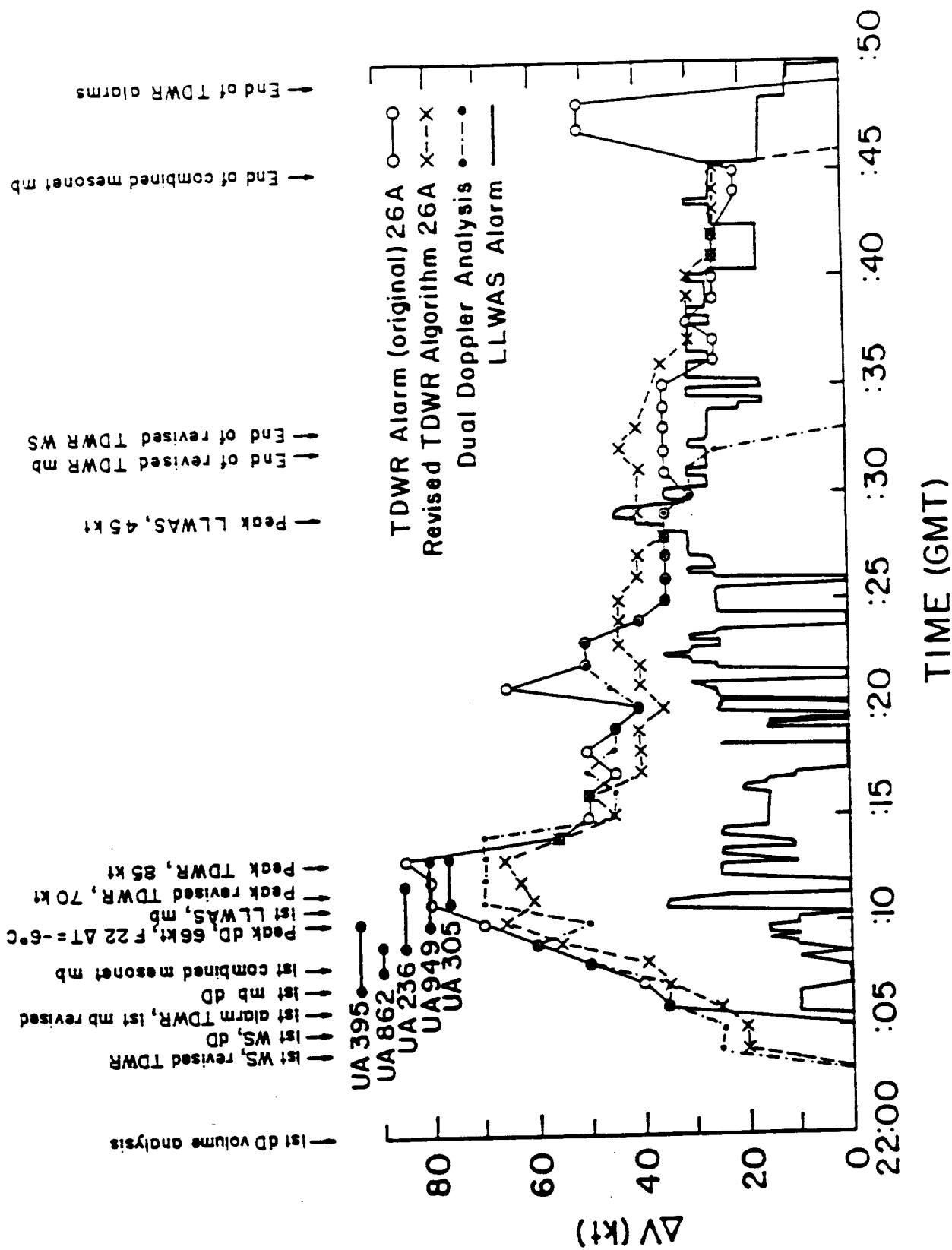
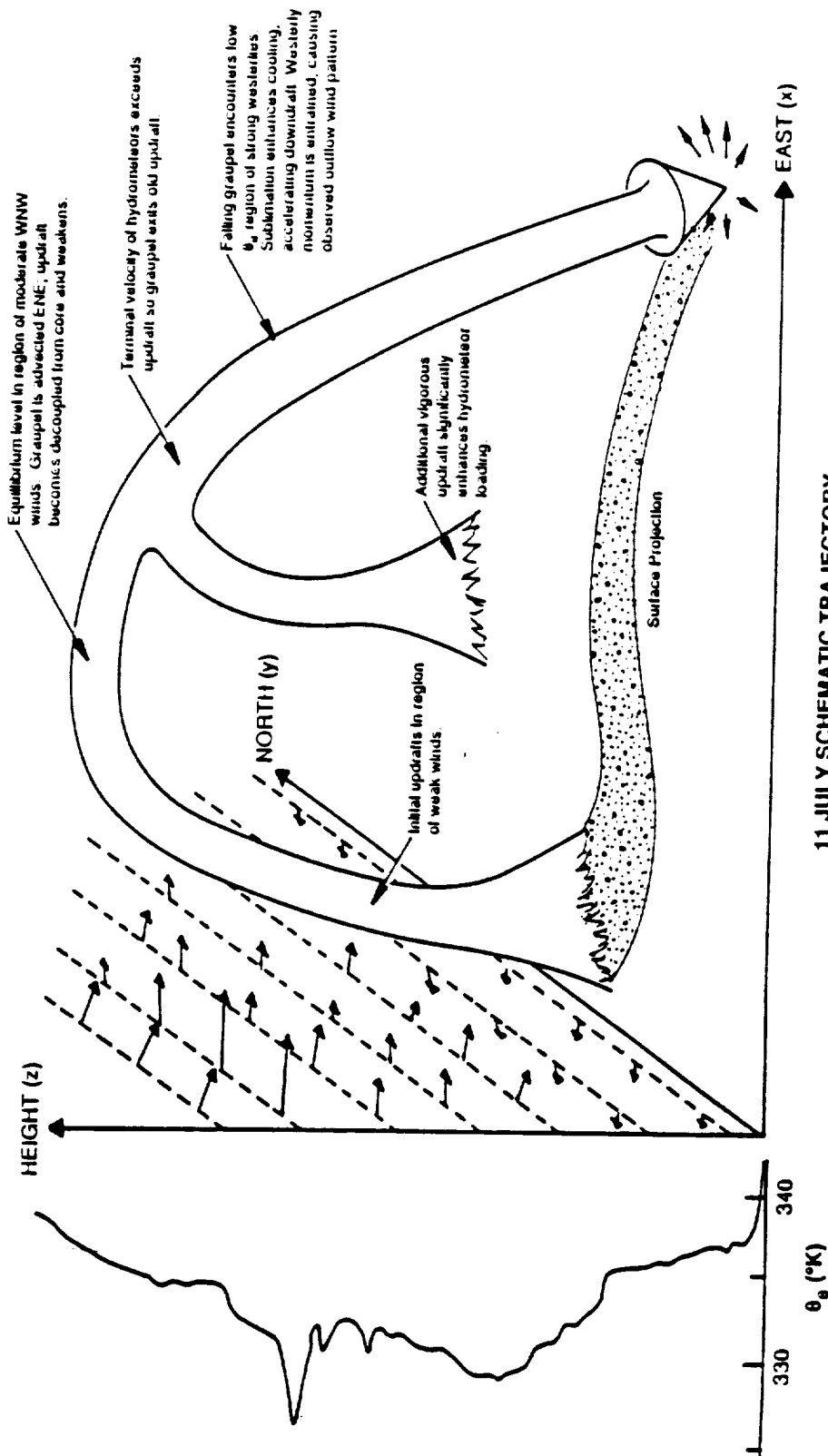
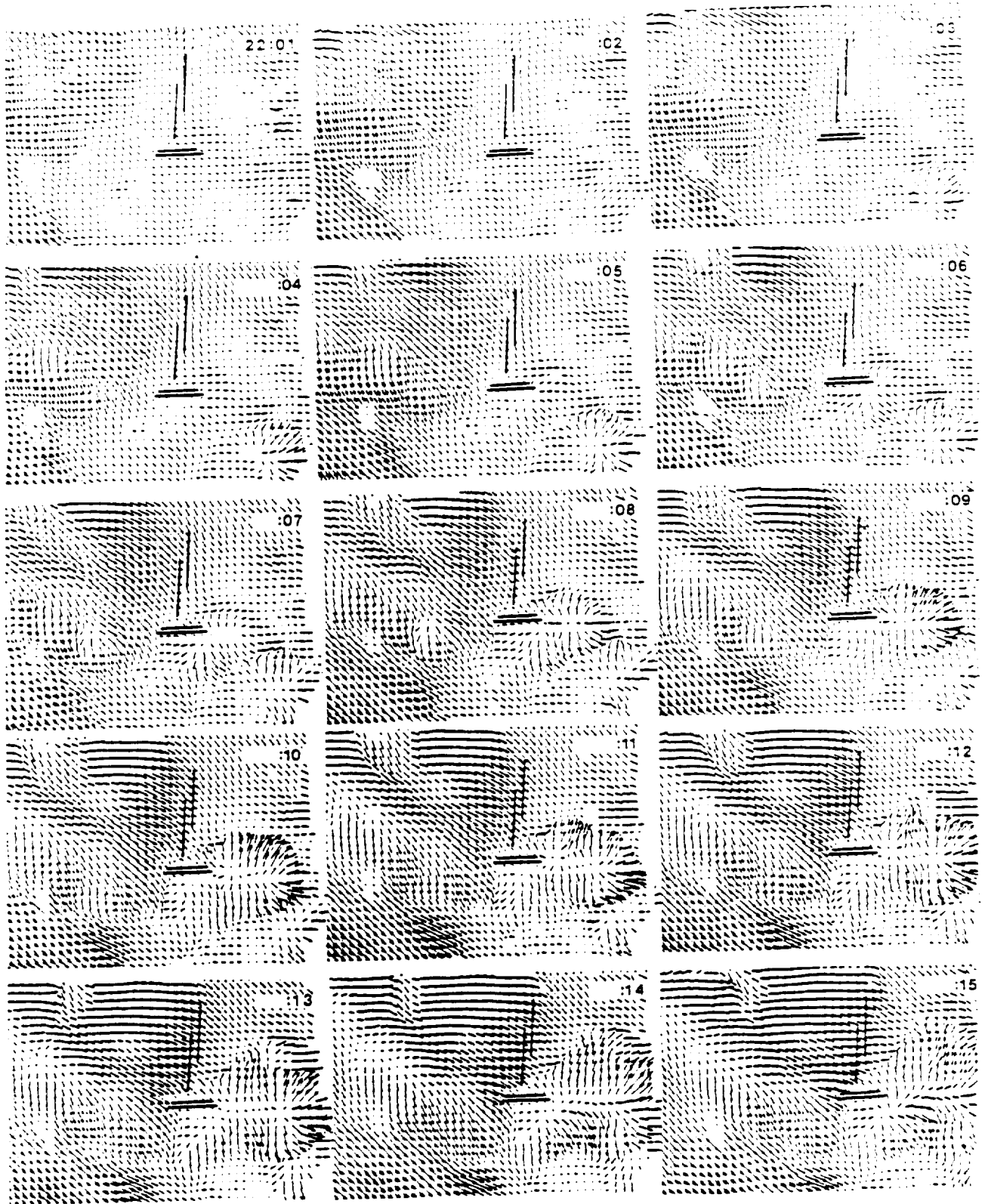


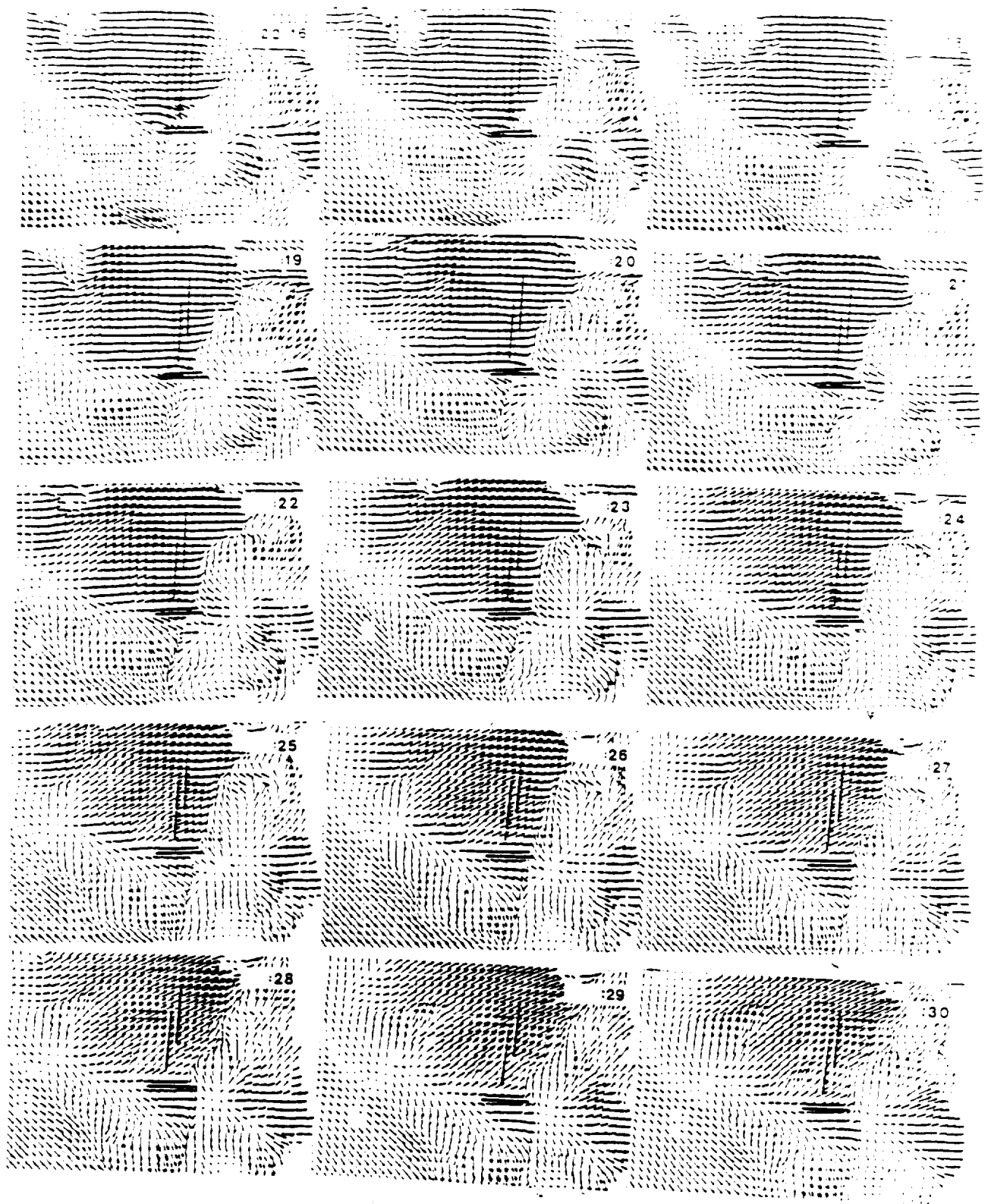
FIGURE 9. Events plotted against time for the 11 July 1988 microburst. A scale for wind shear difference in knots is indicated on the left. Data sources are indicated.



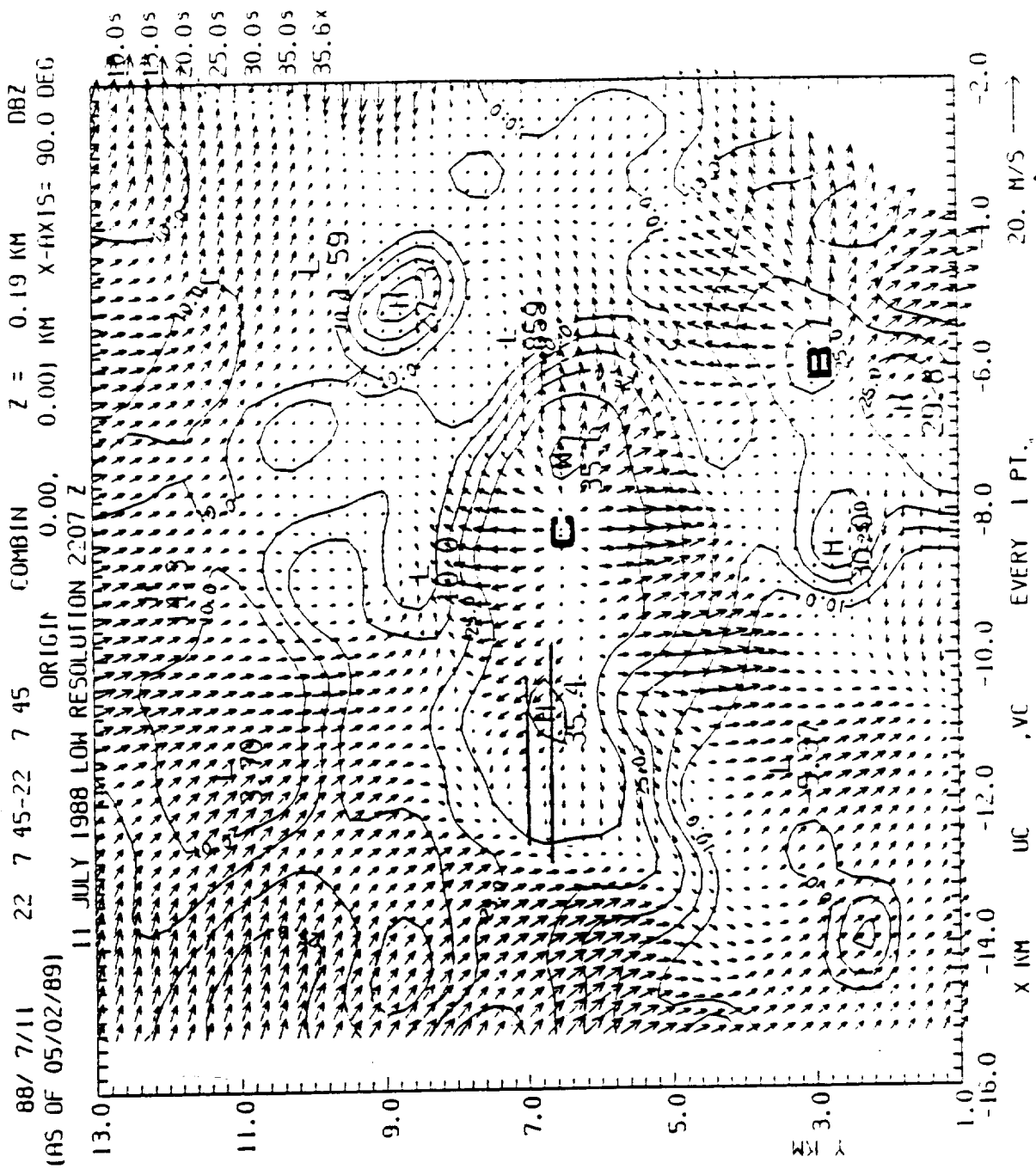
11 JULY SCHEMATIC TRAJECTORY

FIGURE 17. A schematic diagram depicting the evolution of particle trajectories responsible for the 11 July microburst. The sounding to the left indicates θ_e with height near the time of the microburst. Three-dimensional wind structure aloft may be deduced by the wind vectors on the left-hand side of the figure immediately left of the θ_e sounding.

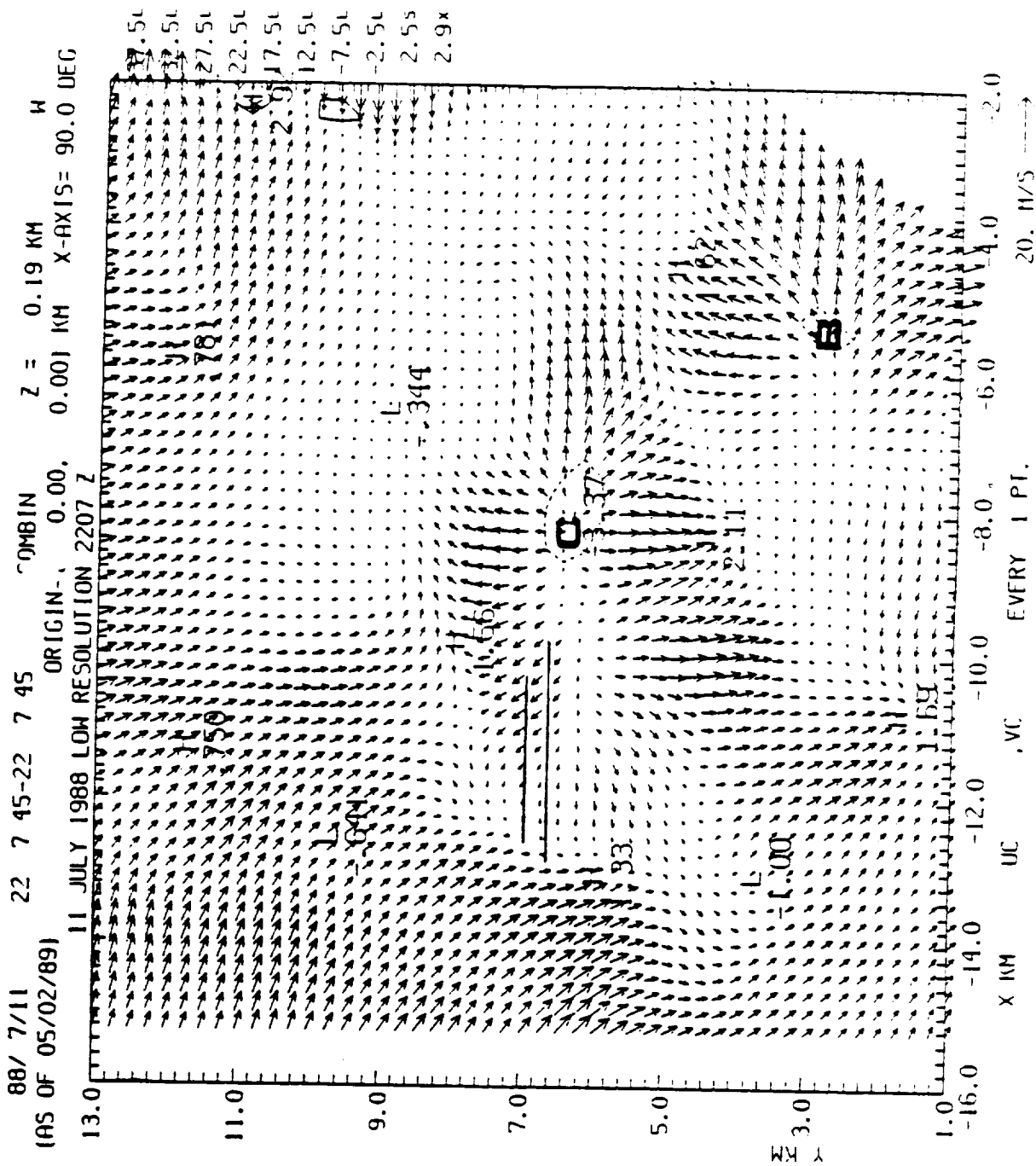


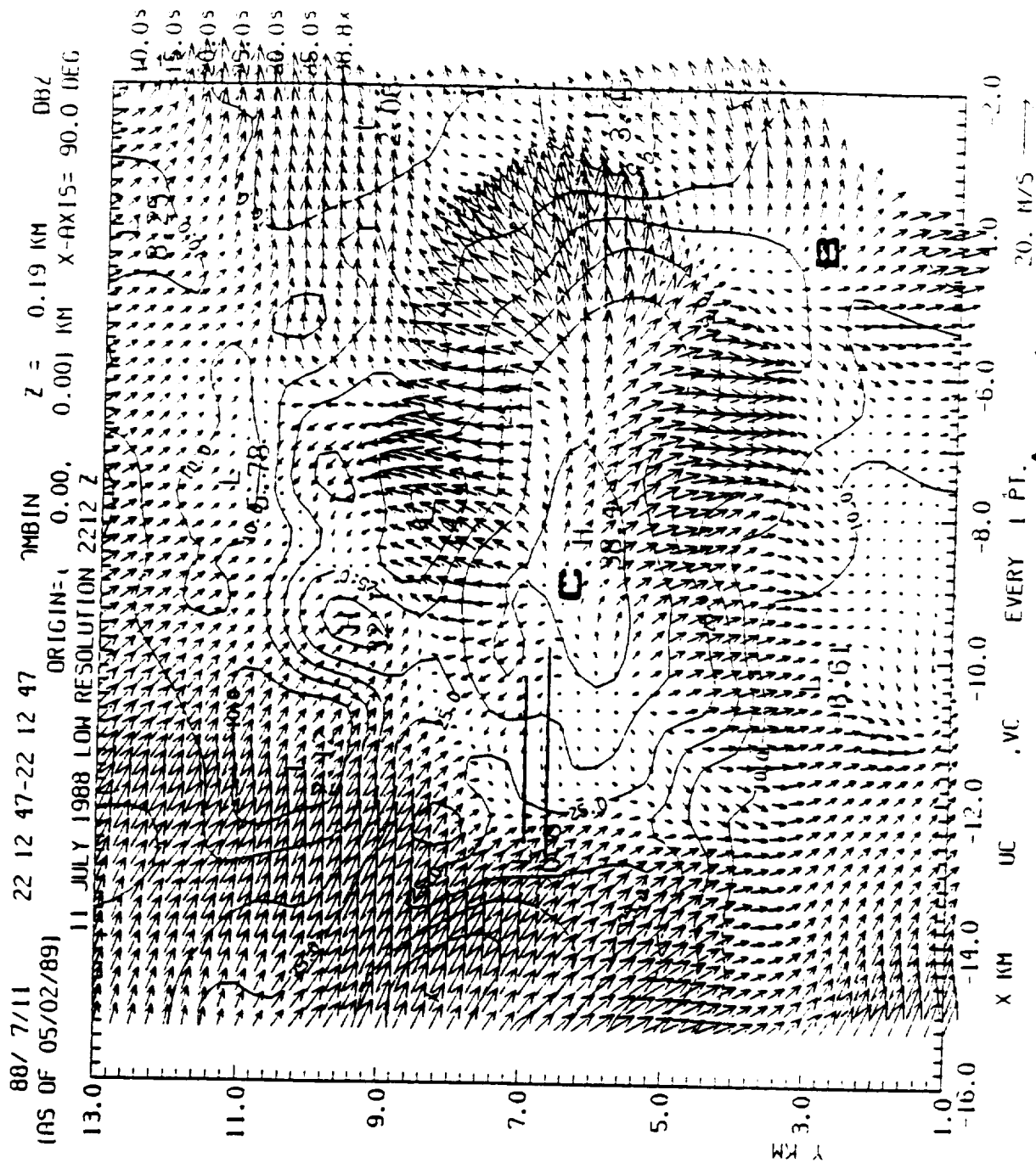


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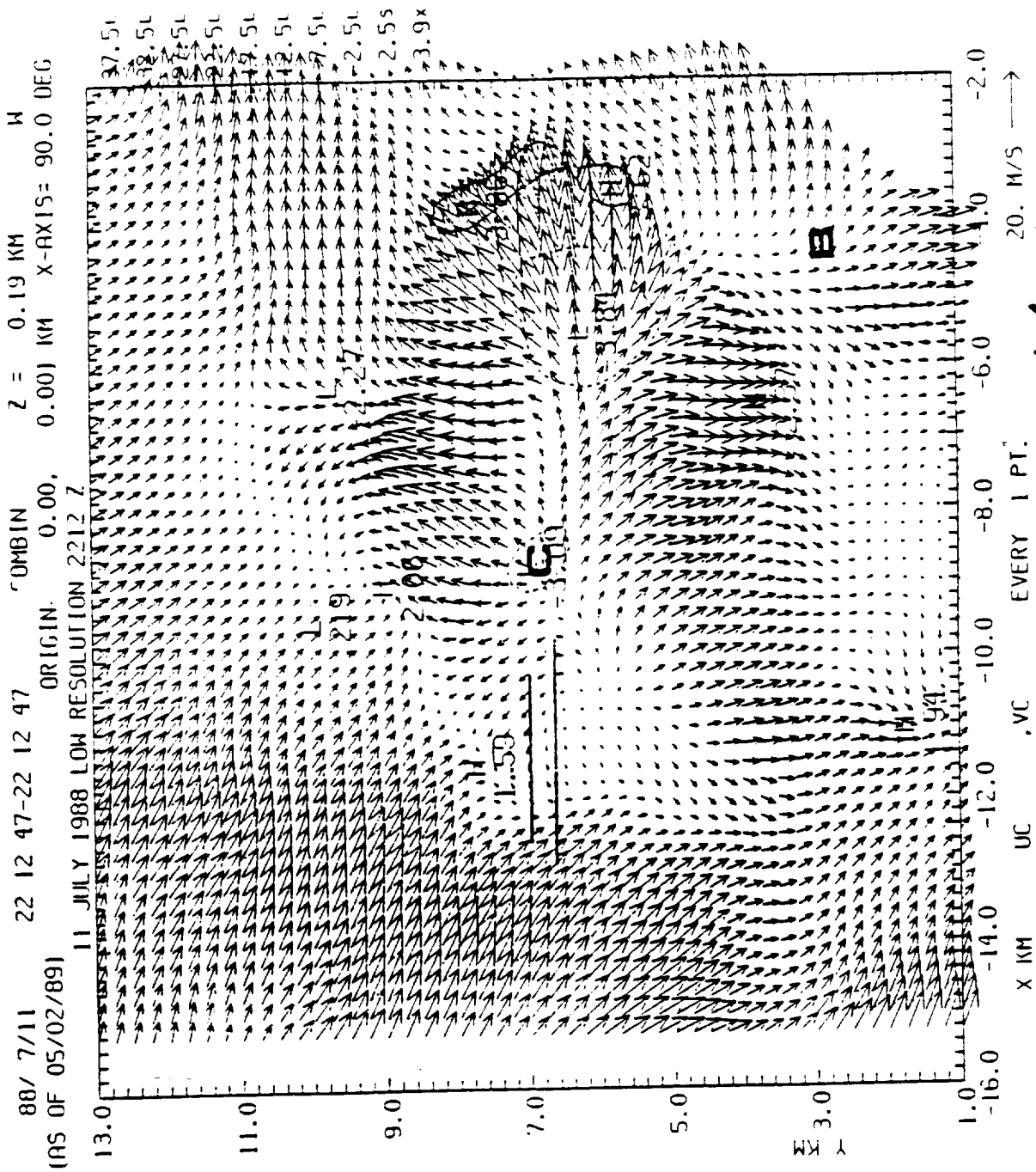


*Dual Doppler Velocities
 Reflectivity*





*Dual Doppler Velocities
 Reflectivity*



if any

Summary, 89 and 90 Activities at Denver:

- 1. Continued development and improvement of TDWR/LLWAS Integration**
- 2. Demonstrated Terminal NEXRAD concept in 1989, program canceled**
- 3. Considerable Interaction with other groups for a better understanding of the July 11, 1988 Microburst Case**
 - > Numerous papers in the literature**
 - > See DOT/FAA/DS-89/19**

4. Reasonably good agreement of f-factor calculations from Radar with those derived from Aircraft

5. Continued development of Nowcasting and Convective Initiation

- > Primary users at Center and TRACON**
- > Prefer Convective Initiation and Storm Motion Vectors**

6. Continued development of Tornado Detection and Forecasting

7. Continued examination of User Interface issues

- > Threshold for warnings (15 Kts)**
- > Size of warning areas (Alarm boxes and alarm shapes)**
- > Perceived over warning**
- > Terminology**

8. Reliable operations during 1990

9. System performance statistics more than acceptable

10. Runway Extension LLWAS is providing good coverage farther from the threshold

11. Enhanced understanding of the relationships between ground based and airborne systems expected during the 1991 tests with the NASA Aircraft flying in the Denver area

The 11 July 1988 Microburst at Stapleton International Airport, Denver, Colorado

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I. Introduction

During the early afternoon of 11 July 1988, while the Terminal Doppler Weather Radar (TDWR) Operational Test and Evaluation (OT&E) was underway, thunderstorms formed over the mountains west of Denver, Colorado, and moved eastward over the plains. By 2130², several cells approached the Denver area. One of the more vigorous of these was located just northwest of Stapleton International Airport. It produced the most intense microburst - 35 m s^{-1} differential - investigated to date using dual-Doppler radar techniques.

The TDWR microburst alarm alerted air traffic controllers to the hazard from 2206-2248. During this time, 4 commercial passenger aircraft penetrated this microburst, fortunately without incident.

The microburst reached the ground several km southeast of the main precipitation shaft of the storm. This behavior differs from that of most microburst case studies reported previously (Fujita 1985). The evolution of the microburst will be examined in this study. Details not contained in this paper will be included in the poster session.

II. Data Sources

The primary data sets used in this study summary come from 2 Doppler radars operated as part of the TDWR OT&E. The Massachusetts Institute of Technology Lincoln Laboratory 10-cm wavelength Doppler radar (FL2) was used as the project test-bed instrument. The University of North Dakota (UND) 5-cm Doppler radar, located about 21 km north of FL2, also gathered data. Scanning patterns of the two radars were coordinated to enable dual-Doppler post-analysis over the airport area (see Fig. 1). Coordinated volume scans were completed every 2.5 min. The lowest effective elevation angle was 0.3° from both FL2 and UND, placing the beam centers approximately 190 m above the center of the airport. Over the airport, both beams were roughly 150 m in diameter.

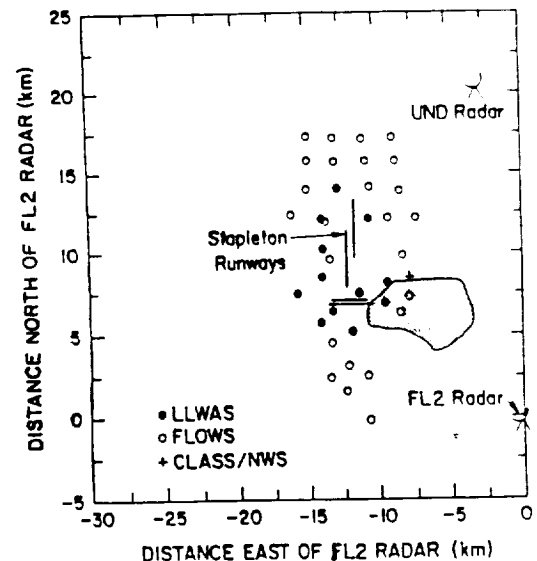


Figure Captions

FIGURE 1. Locations of radars, surface mesonet stations and the CLASS launch site during the 1988 TDWR OT&E at Stapleton International Airport, Denver, Colorado. The airport runways are also shown. The microburst outline (divergence $> 10 \text{ m s}^{-1}$ over a distance $\leq 4 \text{ km}$) near the surface at 2212 is superimposed.

Surface and upper air thermodynamic and wind measurements were also used in this study. The FAA-Lincoln Laboratory Operational Weather Studies (FLOWS) mesonet (Wolfson et al. 1987), consisting of 22 stations, was in place in and around the airport area. This was supplemented by the 12-station Low Level Wind Alert System (LLWAS), which measured winds near the airport runways. A Cross-chain Loran Sounding System (CLASS) launch site was located at the Denver National Weather Service Office adjacent to Stapleton Airport.

¹ NCAR is sponsored by the National Science Foundation

² All times are UTC.

III. Meteorological Conditions

The major synoptic scale weather feature on 11 July 1988 was a slowly eastward-moving shallow trough over the western United States. This feature was barely discernable at 70 kPa and vanished above that level. Winds were generally westerly and were less than 10 m s^{-1} at all levels over Colorado, Wyoming and Utah. This westerly flow advected moisture into the Denver area, which increased in a deep layer extending from just above the surface to over 12 km^3 . A maximum of 1.05 cm of total precipitable water was measured by the National Oceanic and Atmospheric Administration's 6-channel microwave radiometer at Stapleton Airport between 2200 and 2230.

Prior to the storm, conditions near the surface were typical of those accompanying microbursts observed in the Intermountain West (Caracena and Flueck 1987). The temperature-dewpoint spread at the surface was $20 - 25^\circ\text{C}$, with a nearly dry adiabatic temperature lapse rate from the surface to 4.8 km. Above that, a layer of moist air was present. There was marginal moist convective instability, with a Lifted Index of -2 .

Equivalent potential temperature (θ_e) is plotted against height in Fig. 2 for 2 CLASS soundings preceding the storm. Above the moist layer, the atmosphere is quite dry and θ_e decreases. At 7.2 km, a sharp absolute minimum θ_e of 326 K is present in the 2004 sounding, and a relative minimum exists between 4.8 and 5.0 km. The minimum θ_e occurs at the level of a 2°C temperature inversion, the base of which has a temperature of -20°C . Although saturated parcels originating between 7.4 km and around 4.8 km are potentially cold and will accelerate downward, the coldest parcels will originate around 7.3 km and just below 5 km.

Three basic flow regimes exist: light and variable winds from the surface up to 5 km, westerly winds between 5 and 7 km, and northwesterly winds above 7 km.

IV. Analysis

a. Dual-Doppler Analysis Techniques

The CEDRIC analysis package (Mohr et al. 1986) is used for three-dimensional wind field synthesis and analysis. Fourteen volumes were analysed, from 2148 through 2220. The analysis has 400 m horizontal and 500 m vertical grid spacing. The domain extends from 1.8 - 10.8 km (0.19 - 9.19 km AGL) vertically, and 2 - 30 km west, 1 - 23 km north of FL2 horizontally. Stapleton Airport is roughly centered in this grid; the microburst impacted on the southeast edge of the airport, well-centered in the analysis domain (see Fig. 1).

Raw input Doppler velocities were corrected for a deduced storm motion of 10 m s^{-1} from 270° ; resulting analyses shows ground-relative winds.

³ All heights are MSL.

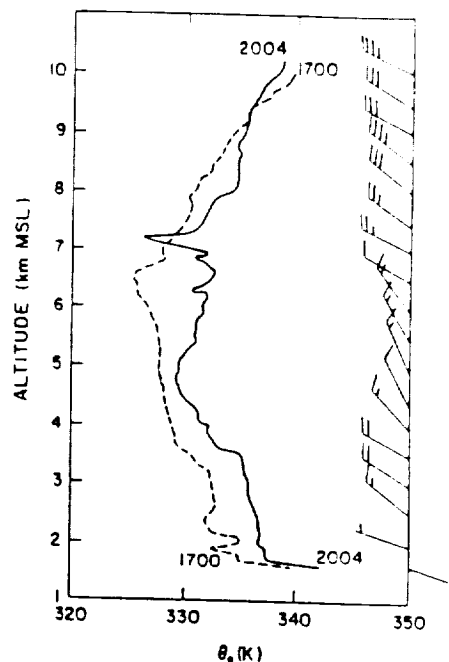


FIGURE 2. Equivalent potential temperature (θ_e) and horizontal winds at 0.5 km resolution plotted against height from the 1700 and 2004 UTC CLASS soundings.

A one-pass Cressman objective analysis scheme was used (Cressman 1959) to map radial velocity components from spherical coordinates to gridded Cartesian space. Before a consistent w component was calculated, the horizontal winds were filtered with 5 passes of a two-dimensional, three-point smoother (Shuman 1955). The resulting analyses have 2 km horizontal spatial resolution at the half-amplitude points.

b. Microburst evolution

The microburst-producing complex originated from two $60+ \text{ dBZ}_e$ cells which formed around 2130 over the mountains 34 km west of Stapleton. These cells grew and moved southeastward.

By 2147, a line of convergence aloft was observed near 6.6 km, oriented northwest-southeast and moving to the southeast. Reflectivity at that level increased just west of Stapleton Airport at 2155, and shortly afterwards FL2 detected large-scale cyclonic shear at 4.6 km over the airport. Surface winds during this time were north-northeasterly across the airport with temperatures of $31 - 32^\circ\text{C}$ across the FLOWS mesonet. The air was fairly dry with 22-25% relative humidity (RH).

As the storm approached Stapleton Airport, the highest radar reflectivity within the storm was above 9.3 km and slightly greater than 40 dBZ_e .

At 2158, 3 reflectivity cores can be identified within the analysis domain, shown in Fig 3a. Core A is the westernmost core extending to the surface. Cores B and C are contained in the comma-shaped region well aloft and southeast of core A (both cores are contained in an area of greater than 33 dBZ_e). Core C was associated with the strongest updraft in the analysis domain, 21 m s⁻¹, and was responsible for the strongest microburst. The perspective used for these figures somewhat obscures core C at this time.

A plume of hydrometeors forms a "bridge" of reflectivity which extends downwind (winds near the radar-detected storm top are from the northwest) from the 3 cores. The updrafts within the cores appear to have penetrated into the layer of northwesterly winds above 7 km, carrying the hydrometeors to the southeast.

Although no direct measurements of the hydrometeors are available for this storm, previous studies in north-eastern Colorado thunderstorms (e.g., Dye et al. 1974)

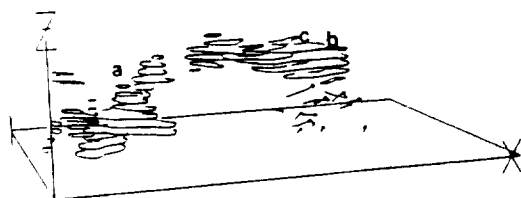


FIGURE 3A. Three-dimensional reflectivity perspective views of the microburst-producing storm of 11 July 1988. The viewer is looking toward the northeast and is located 40 km west and 78 km south of FL2 and is 19.2 km MSL. The 33 dBZ_e is contoured at every 0.5 km AGL. Arrows depict air parcel trajectories during the 2.5 min the volume analysis represents. Analysis time is centered at 2158 UTC.



FIGURE 3B. Same as Fig. 3a, but for 2202 UTC.



FIGURE 3C. Same as Fig. 3a, but for 2212 UTC.

suggest that they were likely graupel. The lifted condensation level from the 2004 sounding has a temperature of -0.5 °C, and the temperature at the echo top level is around -20 °C, both typical of clouds in the area in which ice phase precipitation processes are dominant.

Core A descended to the surface first, well west of the airport area, and represents the main precipitation area of the storm. It produced a weak, large-scale outflow.

By 2202 cores B and C had also extended downward to the surface (see Fig. 3b). Core B produced a small outflow region to the southeast of Stapleton Airport, which was first evident as a 10 m s⁻¹ wind speed differential in the dual-Doppler analysis at 2203.

By 2205, the reflectivity bridge, shown in Fig. 3b, filled in and descended. Most of it appears to have emanated from core C. The surface outflow from core C first appeared at 2205. In 7 min, by 2212, it had reached its maximum strength of 32 m s⁻¹. By this time the outflow from core B is no longer evident.

The FLOWS mesonet station closest to the core C microburst exhibited a temperature drop of 6°C (29 to 23°C), a windspeed increase from 7 to 15 m s⁻¹, and a RH increase from 24 to 43% between 2209 and 2210.

The main microburst maintained a wind speed differential above the TDWR microburst criterion (at least 15 m s⁻¹ over a distance of 4 km or less) until 2241, according to dual Doppler analysis. By 2254 the differential had decreased to less than 10 m s⁻¹, the criterion for TDWR wind shear regions. Elmore and McCarthy (1989) report an average lifetime for microbursts in the Denver area of 13 to 14 min, with a standard deviation of 7.5 min. This microburst lasted 36 min.

As the storm collapsed and dissipated, the surface outflow became quite complex. A gust front, which had been slowly approaching from the northwest, began to interact with the microburst outflow. Several additional less-intense downdrafts merged with the original main microburst, creating a large, complicated multiple-microburst outflow region.

The highest reflectivities descended to the lowest levels of the storm, unlike earlier analyses where they were generally well aloft. Core C remains identifiable through the last dual-Doppler analysis time centered at 2220:47.

Temperatures continued to decrease slowly throughout the FLOWS mesonet as the storm outflow covered the area. The storm complex eventually developed into a weak line and moved southeast.

c. Air Parcel Trajectory Analysis

The history of the microburst was investigated more thoroughly by computing air parcel trajectories backward in time, starting at the time of the most intense outflow. The CEDRIC analysis software used in the analyses subtracts the fall speeds of hydrometeors from the calculated w values, estimated using the observed radar reflectivities. This approximates the vertical motions of air parcels.

Parcels within the main microburst at 2212, at an altitude of 2.2 km (400 m AGL), were tracked to the beginning of the analysis period, 2148.

Three-dimensional perspective views of resultant trajectory ribbons are shown in Fig. 4. Each trajectory terminus is labelled with a vertical bar, and a short dash indicates where each of those bars intersects the surface. The bars then continue downward until they reach 0 km. Trajectory ribbons are illustrated such that rotation along the path is indicated by twisting of the ribbon. Many more trajectories than those displayed were examined, but these are representative of most parcels within the microburst.

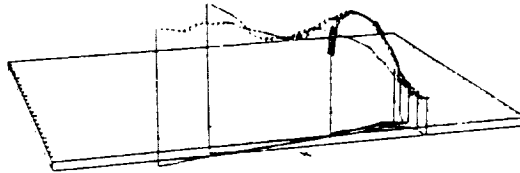


FIGURE 4. Air parcel trajectories obtained from dual-Doppler analysis. The trajectories are shown in three dimensions with projections on a horizontal plane indicated. Each tick mark along a trajectory ribbon indicates 30 s of travel.

Air within the microburst at 2212 originates well aloft and to the west of the surface outflow. All air parcel trajectories remain confined to a narrow east-west corridor between about 5 and 7 km. Early in the analysis period, there are 2 groups of trajectories: those at midlevels well west of the airport and those that are slowly ascending further to the east. These groups merge between 2158 and 2200 at a height of 5 to 7 km, where they intersect the developing reflectivity region. By 2202, the air parcel trajectories are clearly within the region of reflectivity greater than 33 dBZ, and have begun to descend, as shown in Fig. 3b. After this time, the region of high reflectivity rapidly descends and the downdraft accelerates until it impacts the surface between 2210 and 2212, creating the microburst.

Other trajectories (not shown) indicated that none of the parcels within the main microburst originated above 6.25 km, or above the minimum θ_e level. Further trajectory analyses, initiated from the first radar volume and calculated forward in time, showed that air parcels originating above about 7.2 km did not tend to descend. In general, it is likely that no actual air parcels originating above the minimum θ_e level descended to the surface during this microburst. Yet, it is quite clear that the hydrometeors did come from above 7.2 km.

The region responsible for most of the cooling and downdraft acceleration is the broad area of low θ_e located between 5 and 7 km. It appears that the hydrometeors were carried ahead of the region of active convection and into this area of low θ_e , where rapid sublimation and evaporation cooled the air within a narrow vertical layer, intensified the downdraft and created the strong, long-lasting microburst at the surface. Visual observations confirmed that the microburst appeared to have descended from aloft and southeast of the main part of the storm, rather than through the most intense precipitation region.

V. Concluding Remarks

Figure 5 shows a simplified schematic evolution of the main microburst, combining the information gained by following the trajectories of hydrometeors and of air parcels, as discussed in the previous section.

Hydrometeors formed and were carried upward in several strong convective updrafts that existed in a region where environmental winds were generally light. The hydrometeors continued to grow until they became too heavy to be supported by the updrafts and began slowly falling. Strong northwesterly winds near the top of the updraft carried the hydrometeor plume southeast of the active convection. Thus, as they descended, the hydrometeors were carried beyond the main precipitation area of the storm into a level of low θ_e air. Liquid water evaporated and frozen hydrometeors sublimated within a relatively shallow layer, causing the air to become negatively buoyant, whereupon the cooling air accelerated rapidly downward to produce a microburst at the surface.

Acknowledgements

This work was funded by NCAR, the National Science Foundation, and the FAA (through Interagency Agreement DTFA01-82-Y-10513).

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**Controller and Pilot Decision Making
in Transmitting and Receiving Microburst Wind Shear Alerts
from an Advanced Terminal Wind Shear Detection System**

By

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ABSTRACT

Approximately 650 air carrier passenger fatalities caused by low-altitude wind shear have occurred in the United States over the past fifteen (15) years. The most common form of lethal wind shear is the microburst, a strong downdraft and horizontal outflow that occurs near the earth's surface.

During the past decade, a sophisticated microburst detection and warning system has been developed using Doppler weather (wind-measuring) radar and an array of surface wind sensors either together or independently. This system is capable of measuring the headwind-to-tailwind change that a penetrating aircraft is likely to encounter, and it provides air traffic controllers with a simple hazard alert intended for relay to pilots in the immediate takeoff or approach-to-landing mode. The system is intended to induce an early avoidance decision on the part of the flight crew, thus avoiding a potentially catastrophic wind shear accident. The Federal Aviation Administration (FAA) will place this system at approximately 50 major U.S. airports that experience microburst wind shear on a relatively frequent basis.

Operational demonstrations of this detection and warning system in the summers of 1987, 1988 and 1989 at Stapleton International Airport, Denver, Colorado, provided substantial experience regarding air traffic controller and pilot use of this new system. This paper describes three severe microburst events ranging in total wind speed change from 35 to 95 knots, headwind-to-tailwind. Typical airline policy for flight crews receiving microburst alerts was clear: make an immediate avoidance decision.

¹NCAR is sponsored by the National Science Foundation.

Air traffic controller reaction varied from a mechanical recitation of the alert message imbedded in a routine clearance to land (normal procedure) to an urgent relay of a much stronger hazard message followed by a request of the pilot to "say intention," rather than saying "cleared to land." Pilot reactions varied from an immediate decision to avoid the hazardous event (thus totally missing the microburst) to a conscious decision to penetrate the microburst in spite of a clear acknowledgment of the alert.

Human factors related to the ergonomics of these situations are explored, as well as air traffic and flight standards policy issues.

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1. INTRODUCTION

Microburst² wind shear accidents have been responsible for over 35 air carrier accidents in the United States since 1964, resulting in over 650 fatalities (1). In the U.S., the most recent such accident was the crash of Delta Flight 191 at Dallas-Ft. Worth Airport in Texas on 2 August 1985, which resulted in the loss of 137 lives. On 3 September 1989, Cubana de Aviacion Flight 3046 crashed on takeoff from Havana, Cuba, with the loss of 115 passengers and crew and 24 persons on the ground. Evidence strongly suggested that the aircraft encountered a severe thunderstorm-induced microburst.

Since the mid-1980s, the FAA, in conjunction with several research organizations, including the National Center for Atmospheric Research (NCAR) and the Massachusetts Institute of Technology (MIT) Lincoln Laboratory, has developed a wind shear detection and warning system that consists of two separate wind sensor systems. First developed in 1976, the Low-Level Windshear Alert System (LLWAS) recently has been upgraded to detect microbursts. This new version of LLWAS, capable of detecting microbursts, employs 11 to 16 anemometer and wind vane wind-measuring sites situated in the runway proximity to detect diverging wind features near the ground.

More recently, the FAA developed the Terminal Doppler Weather Radar (TDWR), which utilizes the wind-measuring capabilities of Doppler radar to detect microbursts in the airport terminal vicinity. Complete technical details of these systems can be found in the references (2,3).

During the summers of 1987, 1988 and 1989, LLWAS and TDWR were tested operationally at the Stapleton International Airport, Denver, Colorado. In 1989, the microburst detection capability of both systems was integrated in a prototype development phase to provide air traffic controllers and pilots with simple, unambiguous hazard alert messages. The TDWR system can detect microbursts with a high degree of accuracy and with a low false-alarm rate. Specifically, for microbursts having headwind/tailwind differences greater than 40 knots, the probability of detection³ is 98%, while the false alarm rate⁴ is 4%. When a

²A microburst is an intense downdraft and associated outflow, located near the earth's surface, that produces strong headwind-to-tailwind changes for an aircraft which penetrates the phenomenon below 1,000 ft AGL. It is typically situated within thunderstorms but can often occur in less intense convective storms, particularly in dry climates.

³The probability that a valid detection will be made by the system.

microburst detection is made, the system automatically generates a microburst alert and provides an alert message to a computer screen situated in front of the air traffic controller; the controller relays the alert to potentially affected flight crews in either the takeoff or landing mode. A typical approach-to-landing alert reads:

UNITED 226, MICROBURST ALERT, EIGHT ZERO (80) KNOT LOSS ONE
MILE FINAL THRESHOLD WIND TWO ONE ZERO AT TWO TWO KNOTS

A typical takeoff alert reads:

AMERICAN 330, MICROBURST ALERT FOUR ZERO (40) KNOT LOSS ON
THE RUNWAY DEPARTURE END WIND THREE THREE ZERO ONE TWO
KNOTS

During the prototype operational tests of the system, air carriers developed company policy regarding flight crew use of these alerts. In most cases, flight crews were provided with flight safety bulletins that typically stated:

FLIGHT CREWS SHALL NOT CONDUCT AN APPROACH TO LANDING OR A
TAKEOFF WHILE A MICROBURST ALERT IS IN EFFECT.

In addition, air traffic controllers were instructed to provide all flight crews with the alert message whenever an aircraft might be affected by the microburst. However, since inbound flights normally contacted the air traffic controller at or near the final approach fix, the microburst alert was most often issued in association with the landing clearance. On takeoff, the alert was typically issued at the time of takeoff clearance.

These two demonstrations were prototypical, and while air traffic controllers and pilots generally were aware of the operational capability and associated procedures of the system, it was a new, unique system. Consequently, permanent conclusions about air traffic controller and pilot use of this system are somewhat speculative.

In this paper, three microburst events in which valid microburst alerts were issued by air traffic controllers are examined for the purpose of identifying human factor aspects of these alerts. Conclusions and recommendations for possible actions are addressed at the end of the paper.

⁴The probability that an alarm is false.

2. EXAMINATION OF THREE MICROBURST ALERT INCIDENTS

Three microburst incidents are described briefly, followed by a description of pertinent human factors elements:

11 July 1988

At approximately 1600 hours (all times are local daylight time), a microburst developed at 1-mile final to runways 26 Left and 26 Right. TDWR was the only operating system; in 1988 the LLWAS and TDWR systems were not yet integrated. The event initially was detected as a 35-knot loss; it then drifted east and intensified to an 80-knot loss at a 3-mile final. The Geographic Situation Display (GSD) for this event is shown in Fig. 1. The situation steadily intensified for approximately 8 minutes until it began to dissipate. Five air carrier jet transports were in various approach locations at the time, and they received a microburst alert outside the outer marker greater than 3 miles from the runway ⁽⁴⁾. Figure 2 shows the vertical profile of four of these flights during their go-around sequence. The following is a sequential summary of each flight:

Flight 862 (B-737-200) made an immediate avoidance decision based on 40-knot loss microburst alert. The pilot stated that he did not want to make an approach when a microburst alert was in effect.

Flight 395 (B-737-200) was given a 40-knot loss microburst alert at a 1-mile final. The aircraft continued the approach to a missed approach, reaching its lowest point at 50 ft AGL approximately three-quarters of a mile short of the runway. This aircraft encountered the most severe wind shear.

Flight 236 (DC-8) was given a 50-knot microburst alert and continued the approach; it encountered severe headwind-tailwind fluctuations as seen in indicated airspeed. The flight crew executed a missed approach and descended to near 250 ft AGL.

Flight 949 (B-727) continued the approach but made an early missed approach after receiving a microburst alert of a 70-knot loss 3-mile final. The aircraft did not descend below approximately 500 ft AGL.

Flight 305 (B-727) received a microburst alert indicating an 80-knot loss 3-mile final. The crew elected to miss the approach just inside the outer marker.

The following are the pertinent facts associated with these air traffic controllers microburst alert messages:

The first two flights were handled by one air traffic controller. All alerts were given as appropriate, in the vicinity of the outer marker. In these two cases, the alerts were issued with a clearance to land.

The last three flights were handled by a second air traffic controller who relieved the first controller due to a watch change. The third aircraft in sequence (Flight 236) was issued an alert along with a clearance to land.

The fourth aircraft (Flight 949) was issued a microburst alert in the blind without a landing clearance. In this case, the automatic alert appeared on the controller's display, and the controller issued the alert to all aircraft monitoring the frequency, including Flight 949.

The controller issued the most severe microburst alert (80-knot loss) to Flight 305, followed by "say request" rather than "cleared to land."

There were no additional approaches following these first five aircraft; due to the microburst event, the traffic was diverted from the airport for 30 minutes until the weather improved.

8 July 1989

TDWR was not operational on this day. The Enhanced LLWAS system, utilizing 16 wind-measuring sites, protected Stapleton Airport. This system included additional sensors sited to protect the final approach corridors out to 3 miles from the end of the runway. At approximately 1720 hours, a microburst occurred at the north end of the airport on the approach end of runways 17 Left and Right; this event is illustrated in Fig. 3. The following describes the experience of Flight 531:

After being cleared for a visual approach, the captain heard three microburst alerts. The first one indicated a 60-knot loss on a 2-mile final. He continued the approach. Shortly thereafter, the captain heard a second alert, indicating a 95-knot loss 3-mile final. They initiated a missed approach at about a 3-mile final and did not actually experience the event until about a .5-mile final, when they lost 50 knots indicated airspeed and also lost 400 feet in altitude while experiencing moderate turbulence. The missed approach was initiated at approximately 600 ft AGL; the event was encountered at approximately 1,000

ft AGL with a subsequent loss of 400 ft.⁵

The air traffic controller/pilot interaction can be summarized as follows:

The air traffic controller first had an indication of microburst activity: a 35-knot loss on a 2-mile final. When he delivered the alert to Flight 531, the captain asked for substantiating pilots' reports from other aircraft operating these runways. He queried an aircraft that had just landed on Runway 18 (located about 1 mile west); the pilot indicated a 30-knot loss on that approach. This report was heard by the captain of Flight 531 and apparently was used by Flight 531 to consider a missed approach. The controller continued to provide microburst reports to Flight 531 and following aircraft.

Approximately 15 aircraft did not land subsequent to the missed approach of Flight 531. Most aircraft landed at Denver following a hold of approximately 20 minutes; one aircraft diverted to another airport located approximately 60 miles to the south of Denver.

2 September 1989

On this day, a microburst was detected by the integrated TDWR/LLWAS system at 1-mile final to Runways 26 Left and Right. The integrated TDWR/LLWAS system issues consolidated alarms based on products from each independent system. The following describes the flight sequence for two flights, 914 and 2235:

Flight 914, first in line for the approach, received a microburst alert, for 35-knot loss 1-mile final. The captain elected to continue the approach. The event reappeared on the controller's display as a 30-knot loss 1-mile final. The crew continued the approach after a direct question from the air traffic controller querying whether the flight wished to continue the approach. The flight landed with major difficulty, experiencing a 5 g landing that caused structural damage. The captain, upon exiting the active runway, confirmed the microburst and further recommended closing of the runway due to unsafe wind shear conditions.

Flight 2235 followed Flight 914, continued the approach but elected to execute a missed approach on short final.

⁵The captain stated in a post-incident debrief that the wind shear equipment was very good and felt that in this event it probably saved his aircraft.

The air traffic controller experience is summarized:

The identification of the microburst was clear, and all alerts were issued. The controller, in the case of the first aircraft, queried the flight crew regarding their landing intentions, confirming that they wished to land during a microburst alert.

3. ANALYSIS

Several analyses have been conducted for these three events, although only the first one (11 July 1988) has undergone extensive analysis (5). NCAR participated in crew debriefings on the 11 July 1988 and the 8 July 1989 events. The following general analytical comments apply:

11 July 1988

1. The microburst was accurately detected and alerts were issued by two air traffic controllers. However, there was a significant difference in the imperative tone between the first and second controller; the second controller used a more definitive tone of voice.
2. The second controller, upon recognizing the urgency of the alert information, used his controller's discretionary function not to issue a clearance to land for the fourth aircraft (Flight 949). He went further for Flight 305 and added "say request." In this case, we believe that the added query was instrumental in the flight crew's subsequent missed-approach decision.
3. The flight crews typically were unfamiliar with airline policy for microburst avoidance and with the airline flight bulletin describing the operational demonstration. In this regard, it must be recognized that this first-of-a-kind operational test cannot be expected to be well understood by most flight crews. However, the first aircraft (Flight 862) clearly was familiar with policy and made an early avoidance decision.
4. Several aircraft used microburst wind shear recovery techniques (6) during the missed approaches, indicating the value of these techniques; this might have saved Flight 395 from disaster.

8 July 1989

1. The Enhanced LLWAS performed flawlessly in this event, detecting a very dry environment microburst when there were no visual clues for either the flights involved or the air traffic tower controllers. It should be noted that the 95-knot loss measured by this system was the strongest microburst ever measured by any microburst detection system.
2. The controller exercised good judgment by querying adjacent flights for wind shear reports. His actions serve as a model for controller handling of wind shear events.
3. The crew of Flight 531 exercised outstanding judgement and used flight deck crew coordination (as determined in the crew debrief) to make a consensus avoidance decision upon hearing the 95-knot loss alert.

2 September 1989

1. This microburst event was just above the headwind/tailwind threshold for declaring a diverging shear microburst. The event was well detected just above the threshold that indicates a severe wind shear condition. This is confirmation that a 30-knot threshold is an appropriate one, given that the landing aircraft experienced structural damage.
2. The controller strongly suggested, by his queries, that Flight 914 should give serious consideration to an avoidance action (they did not take the suggestion). It should be noted that the controller did not state "say request" or "say intention" as did the controller on 11 July 1988.
3. The crew of Flight 914 made a clear choice to land the aircraft contrary to airline policy and after informal prompting from the controller. The aircraft easily could have been lost.

4. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

The LLWAS, TDWR and integrated TDWR/LLWAS microburst alert systems are a technical success. Once a divergent wind shear event reaches the microburst threshold of an expected 30-knot headwind-to-tailwind differential, the systems work extremely well and produce alarms which are accurate and timely.

The human factors aspects are less successful, and it is in this domain that considerable additional effort is needed. Flight crews continue to need extensive training regarding the impact of microbursts on aircraft and the inadvisability of

penetrating them; standard procedures are needed to reinforce the training. In addition, improved air traffic controller training is needed to standardize controller response to microburst alerts. From the perspective of the scientists who have examined the basic science of microbursts and helped to develop detection capabilities, air traffic control rules and procedures that dictate avoidance are a required next step. Such rules should be consistent with onboard wind shear avoidance avionics equipment.

Controllers could help sensitize pilots to making time-critical decisions by using terminology that triggers the need for a pilot decision based on the presence of a hazardous weather event. The air traffic service should consider testing a cautionary message of "say request" or "say intentions" to encourage strongly a flight crew avoidance decision. This message will need to be examined to see if it adds to controller workload or has other deleterious impacts.

Finally, accurate and timely microburst wind shear alerting equipment is becoming operational in the U.S. Its international use at airports where microbursts are common would be critical to a major mitigation of this hazard worldwide.

5. ACKNOWLEDGMENTS

Cleon Biter, Larry Comman, Kim Elmore, Bill Mahoney, Marcia Politovich and Wes Wilson of NCAR's Research Applications Program played major roles in developing the material presented here. Air traffic specialists at the Stapleton International Airport ATC Tower assisted in obtaining understanding of air traffic control actions and procedures. The flight crews and safety departments of United Airlines and Continental Airlines who were involved in these incidents provided valuable information. This work is funded partially by NCAR, the National Science Foundation and the FAA through Interagency Agreement DTFA01-82-Y-10513.

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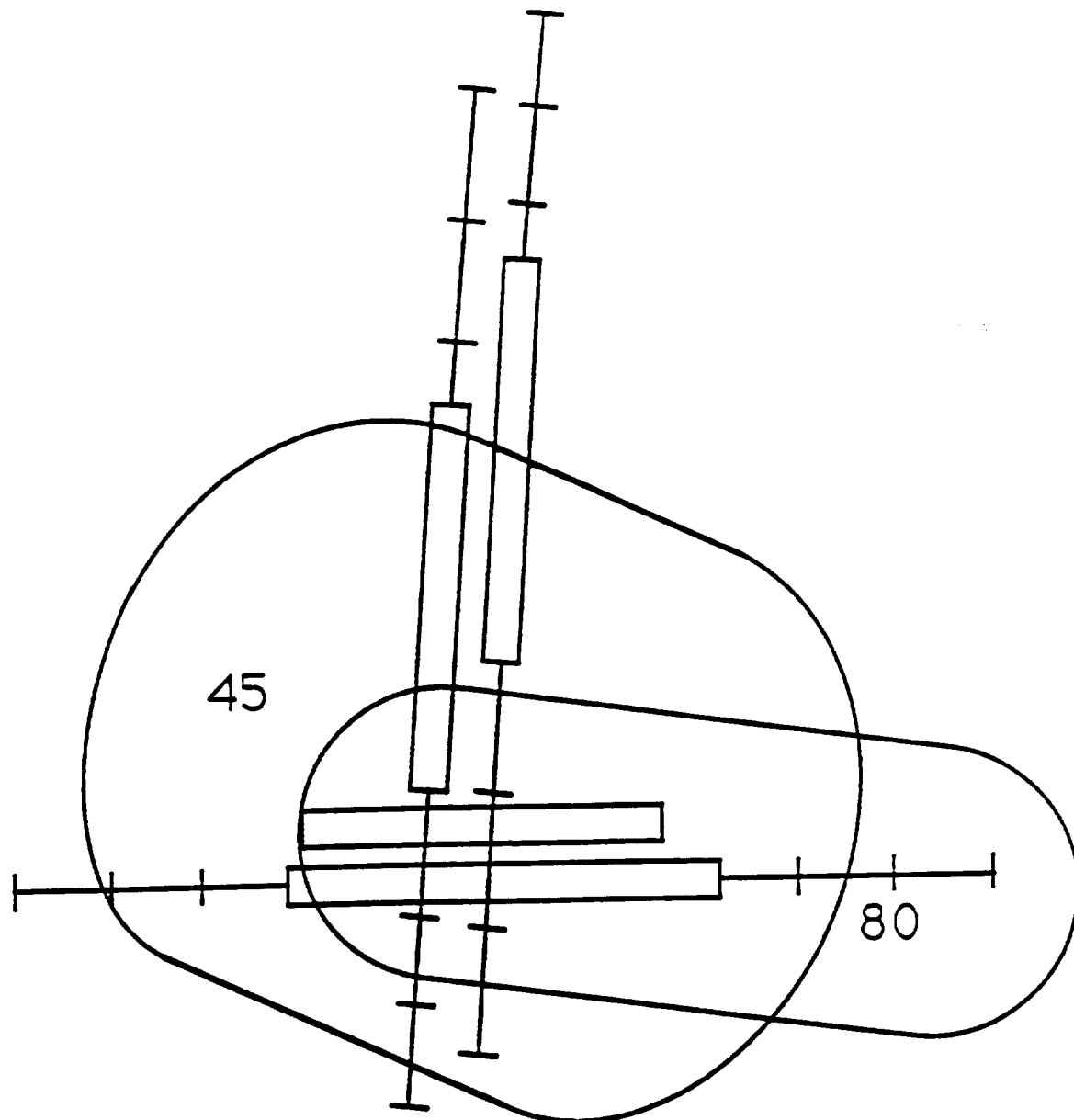


Fig. 1

11 July 1988, 1612 local time, geographic event display of the Stapleton Airport runways with 3 nm extensions off each runway end and microburst events areas shown by ellipses. The 80 knot microburst is shown at it's peak intensity located off the approach end of runway 26.

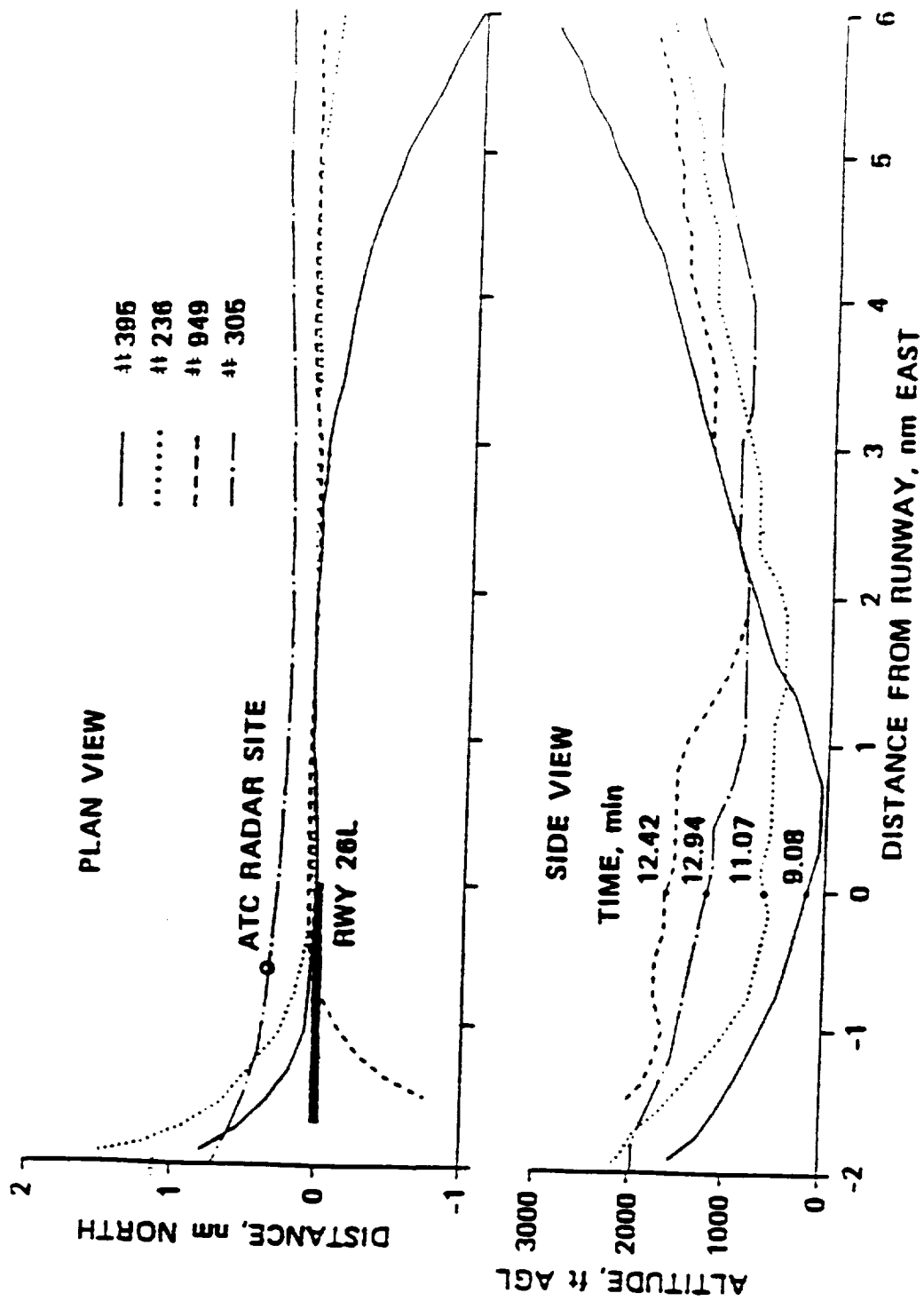


Fig. 2

Aircraft tracks of the four aircraft which penetrated the microburst event on 11 July 1988. The times at which they crossed the runway 26 threshold are shown in the side view with the time being minutes after 1600 local time.

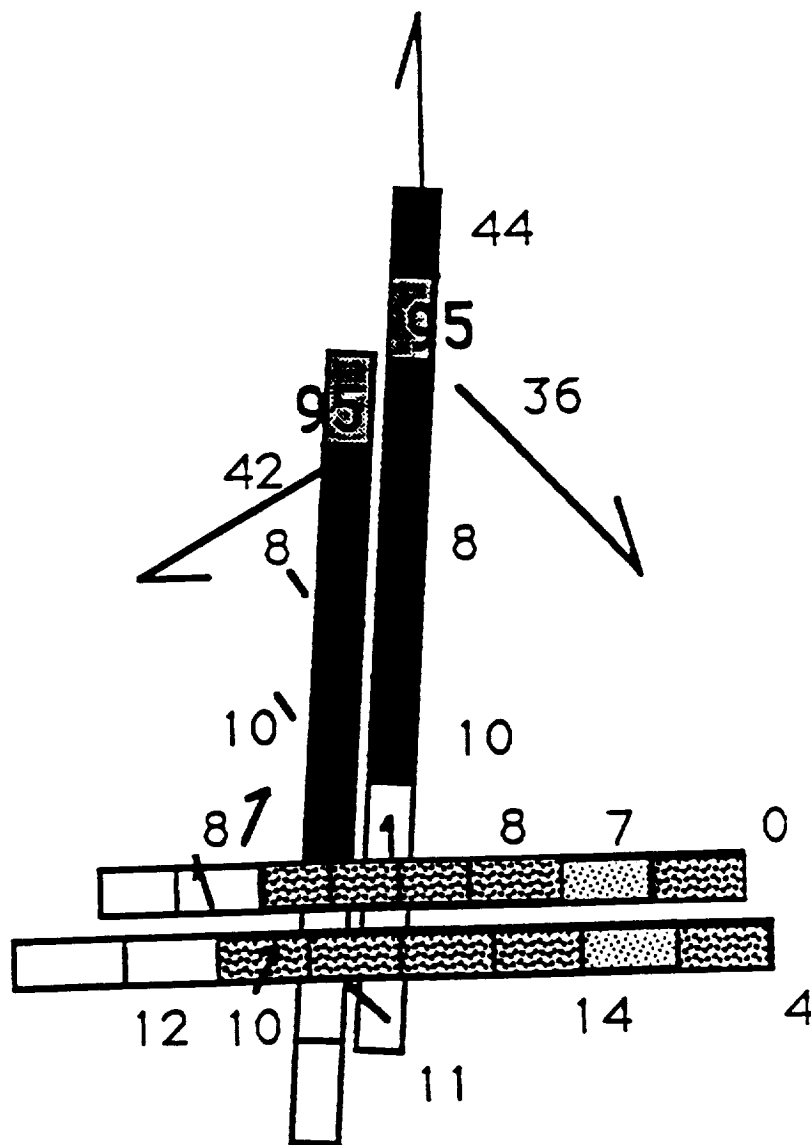


Fig. 3

8 July 1989, 1620 local time, plan view of the runways and three mile runway extensions off all runway ends. The origin of the wind vectors represent the location of the Enhanced LLWAS sensors, the arrows show the direction toward which the wind is blowing and the length and the numbers represent the wind velocity in knots. The 95 knot event on the approach to runway 17 is clearly shown to the north of the airport.

A Status Report on the TDWR Efforts in the Denver Area Questions and Answers

Q: ANDY PECZALSKI (Honeywell SRC) - What is the percentage of dry/clear air wind shear and microbursts that are marginally or not detectable by radar at your test site in summer and in winter? Where could I get this information?

A: WAYNE SAND (NCAR) - Try as we could we couldn't recall the exact number and I'm not sure that we have an exact reference for you either. As best we can recall the number is of the order of 5% that were less than -10 dBZ, which went into some of the requirements for the sensitivity on the TDWR specification to build the system. That is part of the answer and some of it is buried away in a lot of different sources that looked at these kind of events. Of course if there's real low reflectivity and you don't have any other evidence you're not really sure you missed the thing. You're not even sure it's there. Of course when you have them right on the airport it's somewhat easier. We have one known event at the airport in '88 that was clearly missed because of low reflectivity. It was detected by the LLWAS system and totally missed by the TDWR. A number of people were standing there watching it, including the chairman of the NTSB. In the TDWR, the spec as I understand it, is -20 dBZ sensitivity at 30 kilometers. That's how the problem is being approached.

Q: DAVE HINTON (NASA Langley) - You indicated that pilots were concerned with a 10 to 15 knot airspeed loss. As Professor Hansman pointed out a 10 knot airspeed loss will require wind divergence of at least 20 knots, more depending on the diameter of the event. Could you elaborate on how you use pilot comments concerning airspeed loss to establish TDWR alarm thresholds that are based on wind divergence.

A: WAYNE SAND (NCAR) - Well, fundamentally this is input from the TDWR/LLWAS user working group which consisted of a number of pilots and controllers and other people associated with the problem. It was counsel received from airline operations, pilots, all of those kinds of people that said they wanted to know when the system detected a 15 knot event. We're still troubling with that threshold value. We're getting feed back from pilots saying they're experiencing what they consider to be significant wind shear events with a 10 knot change. So it's a debatable issue. We set that threshold based on "professional" input from people who thought they knew what they wanted. We continue to assess that threshold.

Q: FRED REMER (University of North Dakota) - I believe that people are avoiding wind shear at Denver but the problem there has been well publicized. How are they responding at other locations?

A: WAYNE SAND (NCAR) - Generally, pretty good. What we're getting back on questionnaires from Orlando this year and from Kansas City last year is generally favorable. The pilots are reacting to that and we see the curve going in the right direction there, at least in our opinion. We have more people avoiding things that are called microbursts everywhere.

Q: FRED REMER (University of North Dakota) - ATC is an active participant in the Denver TDWR program, how would you qualify their participation?

A: WAYNE SAND (NCAR) - They are very active participants. The people in Denver are a good group to work with. The air traffic controllers, supervisors, and the center weather

service unit people are all very interested in what's going on and they all have a lot to say. I'd like to think we listen to all those people and certainly consider all of their input.

Q: FRED REMER (University of North Dakota) - What I found in Florida is that they're not able to handle the situation before a gust front or a microburst occurs. For example, a gust front comes through and all the airliners that were lined up, taxi down to the other end of the runway and get ready for departure. Then the shear is gone and we have environmental conditions again and they taxi back down to the other end of the runway where they were originally. So the question I was asking is, are they able to accommodate that? Do they predict that?

A: WAYNE SAND (NCAR) - In a word, yes. In Denver, they've learned how to deal with that. This 10 and 20 minute wind shift prediction product, which gives them a velocity vector of the wind to be expected behind the gust front, is used by the supervisors to decide when to change runways and if runway changes will be required. They in fact will start taxiing people to different runways. They'll say, hey, we can take airplanes up to this guy, the rest of you guys go to the other runway, whatever it is. In my view they're getting very good at using that wind shift prediction product to reconfigure the airport. Denver, of course, is a little bit different than Orlando, with orthogonal runways.

UNKNOWN - The LLWAS winds are on the GSD for the traffic supervisor at Denver. They were not put on the GSD in Orlando. So that the display of a wind map from LLWAS, which makes the runway management more effective, was not available at Orlando.

WAYNE SAND (NCAR) - That's another word to speak for integration at some level. Putting those wind vectors on the GSD very rapidly builds confidence in the wind shift algorithm.

STEVE CAMPBELL (MIT Lincoln Laboratory) - We did have the wind shift prediction product at Orlando this past summer. Part of the problem may be that the people at Orlando haven't had as much use, or maybe hadn't built up a confidence factor yet, whereas it's been available in Denver for the past couple of years. It's worth noting, one of the main economic justifications for TDWR is the ability to predict these wind shifts. It's one of the things that controllers in general seem very enthusiastic about along with the storm motion.

WAYNE SAND (NCAR) - A lot of these new enhancements that are coming along for the system are pretty well received. I think from day one at Denver, when we started putting up wind shift products they were well received. They figured out right away how to use that. It was very quick. But, as John pointed out, it probably has something to do with the vectors that are on there from all the LLWAS sites. That gives them a lot of confidence in what's going on.

Q: ROBERT OTTO (Lockheed) - It was stated that there is "reasonably" good agreement between calculations of F-factor from radar and those from aircraft. Please clarify. What are the quantitative comparison numbers and how are they determined?

A: WAYNE SAND (NCAR) - There is some arm waving that goes into that. You have to make some assumptions about the vertical motions. What's used to do that is the continuity equation. It's coming down, it's got to change directions and go the other way. So it's a continuity argument used to compare between the two terms in that equation, the horizontal term and the vertical term. There are a number of people who have attacked that problem. We've done some of that at NCAR, the people here at NASA Langley have done quite a bit of it, and the people out at NASA Ames, Rod Wingrove, has done some of those

kinds of things. There is some literature now that discusses those kinds of things. You saw a number of those displays yesterday and today where you're looking at radar computed F-factors versus airplane computed F-factors and generally those track pretty well. I think that was the basis of my comment.

Q: PAUL ROBINSON (Lockheed) - This question relates to operational procedures concerning TDWR procedures on the 11 July microburst encounters. My impression is that the aircraft were only notified about the microburst after being cleared onto the approach and pilot reports seem to be absent.

A: WAYNE SAND (NCAR) - Absolutely true. They were absent. Bob Ireland is here and that was one of the issues that came out of the United report. With that is a very strong encouragement for pilots to give PIREPS. There were none in that event.

Q: PAUL ROBINSON (Lockheed) - Should the shear information have been communicated to the pilots before being cleared onto the ILS?

A: WAYNE SAND (NCAR) - The answer to that is probably yes. In fact, the way the system was working then was that the information was available to the final controllers in the tower and in the TRACON. Those are the people who are talking to them basically before the outer marker. So the flight crews didn't have access to talk to somebody who had the information available right in front of them until they were at the outer marker. Now, based on that case and some additional effort that's gone on since then, there is a little more activity in the TRACON with the supervisors now trying to get that information to controllers. There are more displays of alpha numeric information in the TRACON so that controllers have an option to look at that. But I don't believe there's still any obligation to give that information out from the TRACON positions. It still is the responsibility of the tower controller to give that information to the flight crews once they come over to tower, which at Denver is typically about the outer marker. Were PIREPS available? No, they just weren't available.

Q: ROLAND BOWLES (NASA Langley) - What is the termination criteria for TDWR alerts?

A: WAYNE SAND (NCAR) - It's a relatively simple termination criteria. It's when the system senses that the total wind change across the detected event goes below 30 knots. That is when the event terminates. Now the question is much more complex than it sounds on the surface because by the time it gets to that point the event typically gets somewhat bigger. The real question is, is that waiting too long because the level of shear hazard at that point may be small. It's the delta V over delta R that's important to the airplane. The delta R often times gets quite big. So it's a question of when you cut that off. At the moment we're cutting it off when the delta V goes below 30 knots. That may or may not be correct and that may be one of the ways we can also clean up the time that the system is alarming. It's something that we continue to try and look at and we don't have an answer for yet.

Q: BOB IRELAND (United) - For use in writing SAE-S7 standards for look-ahead systems, please define dry conditions, e.g., dry microbursts, both in terms of reflectivity and other parameters such as relative humidity.

A: WAYNE SAND (NCAR) - I don't know where you draw the line. The ends of the spectrum are pretty easy but where you draw that line I don't know.

UNKNOWN - To call it dry versus wet is arbitrary. You can draw a line anywhere you want. The fact is, the spectra of microbursts go from very dry to very wet and it's continuous.

WAYNE SAND (NCAR) - I'd hate to offer an opinion on that. I would refer back to the analysis of the July 11 case for just a comment. Most of us think of July 11 as being a dry microburst, yet it was raining at the airport and there were reflectivities in the high 30s, which starts to get up to crowding red on an airborne display. In that one we all refer to it as dry, yet on many radars you'd have seen dots of red in that particular event. So, I hesitate to draw that line standing up here on the podium. I don't know where it belongs.

BOB IRELAND (United) - That was probably a little unfair to ask you at the last minute. It just came up last week at the S-7 meeting and we want to say in our document that we want systems to work in both dry and wet conditions. We didn't feel that we had the collective knowledge to draw a line, a reasonable line. We need to say that it's got to work from a certain minimum to a certain maximum.

MARILYN WILSON (MIT Lincoln Laboratory) - The dry microburst was defined as 35 dBZ or lower because we looked at rain gauge measurement in Denver to see when measurable precip was actually detected. For the drop size distributions found in the Denver area, 35 dBZ was most commonly the line. If the reflectivity was lower than that, the rain gauge at the surface measured no rain. But, on a day like July 11, 1988, there was measurable rain. So it's not a hard and fast thing. It depends on what that dBZ is giving you. Those are also surface reflectivities. If you look aloft you could see a higher reflectivity. That's sort of the maximum reflectivity at the surface. What the minimum reflectivity at the surface is, no one has really catalogued.

BOB IRELAND (United) - I guess what I'm concerned about is, in the absence of precipitation, is there still reflectivity? I'm talking about when there is not precipitation but we have a dry microburst, what can we use as a measurement?

MARILYN WILSON (MIT Lincoln Laboratory) - There is precipitation there and there is measurable reflectivity there, it's just that there's a few big drops and it skews this Z number that the radar measures up to a higher reflectivity, like 20 dBZ, even though there is nothing measurable by a rain gauge. There is rain in the air it's just sparse. There is also dust in the air.

UNKNOWN - What we were trying to do on the S-7 committee was to define what an airborne wind shear system must detect. For example, for the IR we picked up some numbers as to the level of rain through which it must look. We needed the other side of the equation for what a LIDAR must do and what a radar must do, in terms of what performance it must meet from an airborne platform to be acceptable. So the question was, if a number like 5% of microbursts are very, very dry, is that something that an airborne radar must detect. Equally, must an IR or a LIDAR look through X rain? That's where we were trying to go with it. We were trying to pick some numbers. Our committee was concerned about what is it that our system has to do. Let's define some system requirements. If people are going to be flying into Denver and if they've got an airborne radar low level wind shear detection system and there are dry microburst, we've got some specs for people to shoot at.

WAYNE SAND (NCAR) - It's certainly a fair question and I would suggest that that's something we probably have to get our heads together between NCAR and Lincoln Labs, at least, and try and provide you with a number. I think it's a matter of, as you say, setting

a definition and somebody has to do it. Maybe we have more data than anybody else between us to try to come up with that number. Let us get back to you for the committee on that. We'll work the problem and see if we can come up with at least our best estimate.

Session V. TDWR Data Link / Display

Thermodynamic Alerter for Microbursts
Dr. Peter Eccles, MITRE

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Thermodynamic Alerter for Microbursts (TAMP)

Peter J. Eccles

MITRE

The MITRE Corporation has an internal research and development program, called MITRE Sponsored Research (MSR), funded directly and only by MITRE. All MITRE Technical Staff are invited to submit proposals annually for competition for the funds allocated for MSR and related work.

In the middle of 1986 a Radar Meteorology Conference was held at Snowmass, CO, in which several workers used surface temperature depression data for confirmation of meteorological radar observations of microbursts. A proposal to engineer a fast, inexpensive, comprehensive meteorological sensor suitable for deployment in arrays, to build an array system using these sensors as building blocks, and to analyze the results from the system was submitted for consideration by MITRE at the end of 1986.

Subsequent to some immediate and continuing revision, this proposal became an MSR project, with initial funding in October, 1987. This talk describes this project.

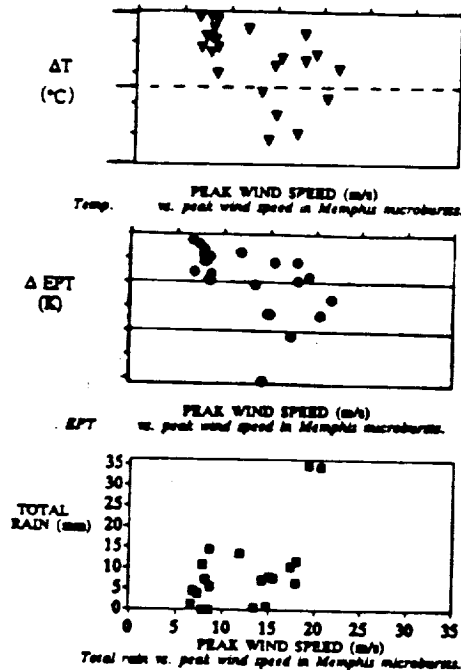
Background

- **Microbursts + other factors**
 - crash aircraft taking off or landing
 - close runways
 - cause delays
 - force alternative airport landings.
- **Microburst detection, location and measurement**
 - will enhance airport usage and safety.

MITRE

Microbursts, streams of rapidly moving, downwardly directed air, are a principal cause of wind shear hazards. The air within a microburst cools rapidly due to water drop evaporation and melting hail, both of which maintain negative buoyancy in the air and propel it to the ground. Microbursts are always associated with clouds and principally with severe convective storms, though microbursts have been observed beneath virga-like precipitation. Microbursts are typically elliptical in shape and initiate relatively high in the atmosphere where heavily water-laden air can have diameters of ten km or more. The negatively-buoyantly maintained rapid downward acceleration of this water-laden air causes a microburst to become narrower as it approaches the ground so that it may have a diameter of less than a kilometer near the ground. When the air in a microburst strikes the ground, it scoots out horizontally in a diverging pattern from a central point (or nadir).

Due to the strongly divergent air, a moving aircraft first experiences a headwind, which increases lift, rapidly followed by a tailwind, which reduces lift by reducing the relative speed of the aircraft. A significant loss of altitude can occur which, depending on the altitude of the aircraft, can cause a crash.



MITRE

Initial interest in this research stemmed from the widespread use of surface temperature loss data (Wolfson) for confirmation of meteorological radar observations of microbursts. Thus, it seems appropriate to locate microbursts from temperature loss data alone. Temperature surface arrays have the promise of being far less costly than radars. Radars have the property of covering large areas, but this may be an inappropriate use when the area required to be protected is more nearly a point, namely an airport. It is well known that the military philosophy for weather prediction is to concentrate on point prediction (such as airfields) and this mind set is also the appropriate one for microburst measurement.

Srivastava, Proctor and Wolfson have shown that temperature does not always decrease. For some dry microbursts temperature increase is expected. However, equivalent potential temperature, θ_E , another atmospheric parameter appears to have much more potential than temperature as a microburst indicator. θ_E is a conservative quantity. If θ_E is measured for an isolated air parcel, it can be tracked much as if it contained a radioactive nuclide in it, because its θ_E does not change with time. Thus if θ_E is monitored over a field, and displayed on a PPI-like display, we have an economic method of examining the near-surface atmosphere.

LONG TERM IMPACT

- HIGH CONFIDENCE OF DETECTING, LOCATING ALL MICROBURSTS
- ECONOMIC OBJECTIVE: AFFORDABLE LOW COST
- WORLDWIDE CONSCIOUSNESS OF MITRE'S COMMITMENT TO AIRPORT SAFETY
- POTENTIAL SPONSORS
 - GOVERNMENT AGENCIES RESPONSIBLE FOR AIRPORT SAFETY
 - FAA
 - MAJOR AIRPORTS
 - MINOR AIRPORTS
 - AIRPORT MANAGEMENT, WORLDWIDE

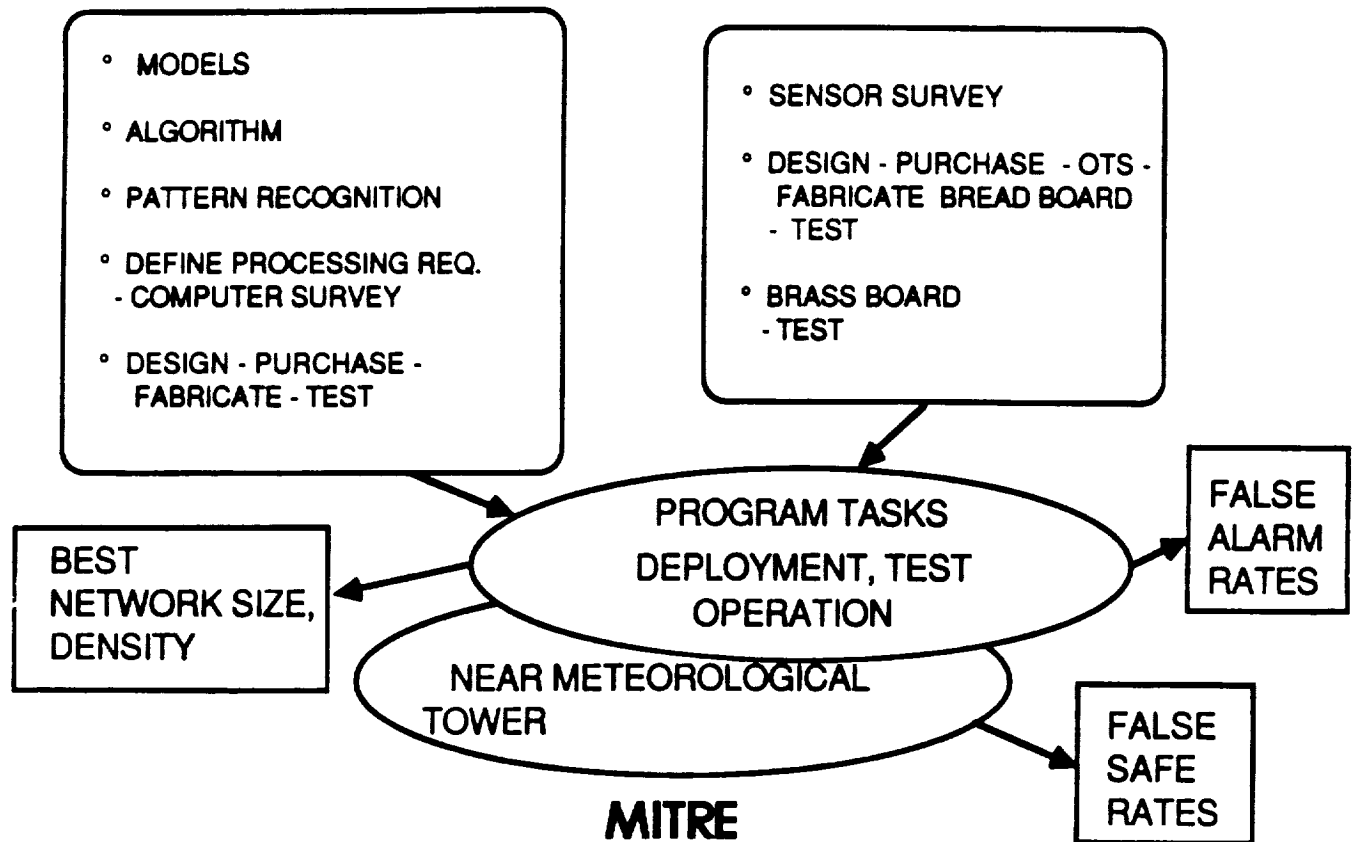
MITRE

Since its formation, the MITRE Corporation has been associated with Air Traffic Control (ATC). We are aware of the absolute requirement for high quality in the reliability, accuracy, precision and availability of equipment for ATC in that these provide confidence to the users: flight specialists including ATC specialists and air crew. Our objective was to show that both the equipment and the associated algorithms computing θ_E had these properties. The sensors and the equipment would be inexpensive, solid state, and solar powered. The equipment, displays and archiving would be based on standard IBM-compatible personal computers (PCs). The success of this very simplified wind shear detection system would affirm the company's interest in sensible, simplified but confidence-inspiring ATC equipment.

The experimental plan was to deploy a tight array of reliable solid-state meteorological sensors around an airport, to set up a digital data recording system and to operate this in a hands-off mode. In this first instance the data would be analyzed off-line, though it could be used for operational purposes, given the appropriate analysis and display capabilities.

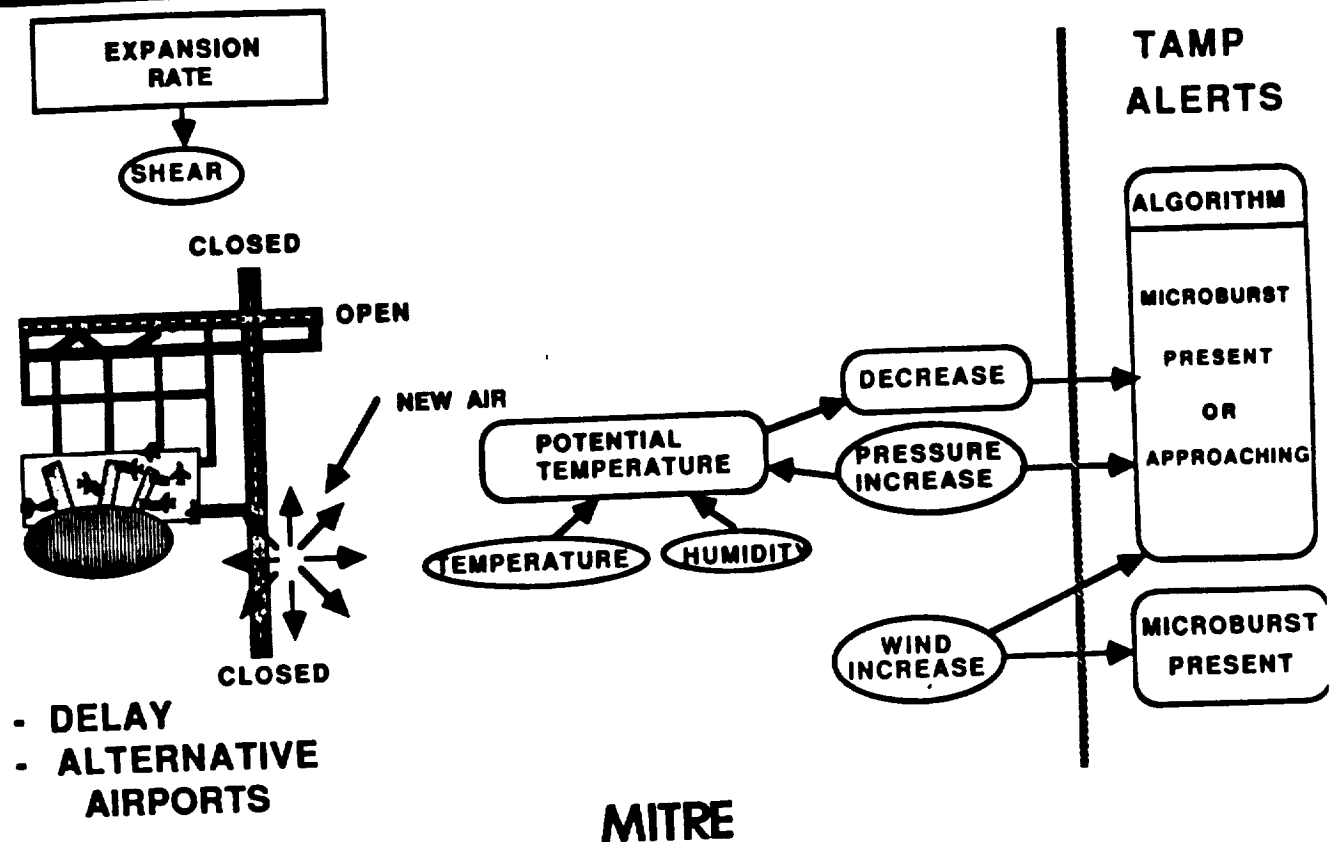
Other objectives of this MITRE-funded research were to have a high confidence of detecting and locating all microbursts, and to work to deploy operational θ_E -measuring arrays in places which there are no plans to detect microbursts at this time, such as secondary, General Aviation and third world airports.

APPROACH



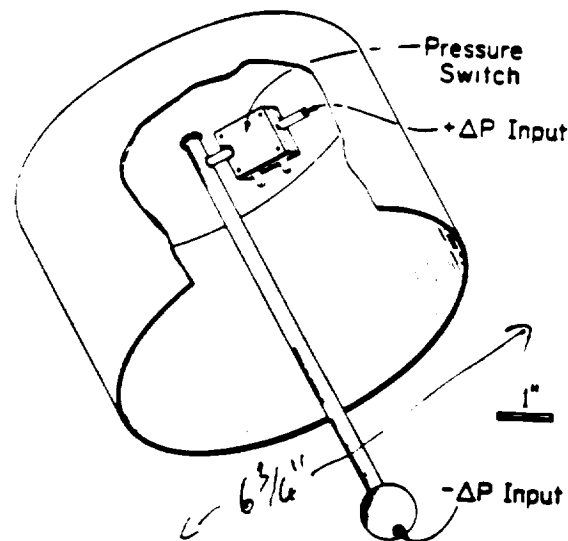
The MITRE approach to this problem was very standard. One of the first products was the development of a complete system specification. The slide is self-explanatory. It sets out the various major objectives including the detailed planning, purchasing and equipment refinement for the development and test of any large system including this thermodynamic alerter for microbursts.

Thermal Alerter for Microbursts Prototype (TAMP)



Since θ_E is conservative, new air from aloft will have a different θ_E from air at the ground. Therefore, a pool of different (almost invariably lower) θ_E will appear as a rapidly expanding pool within the currently present, nearly uniform, θ_E . Proctor has shown models of near-surface changes of this type due to temperature alone.

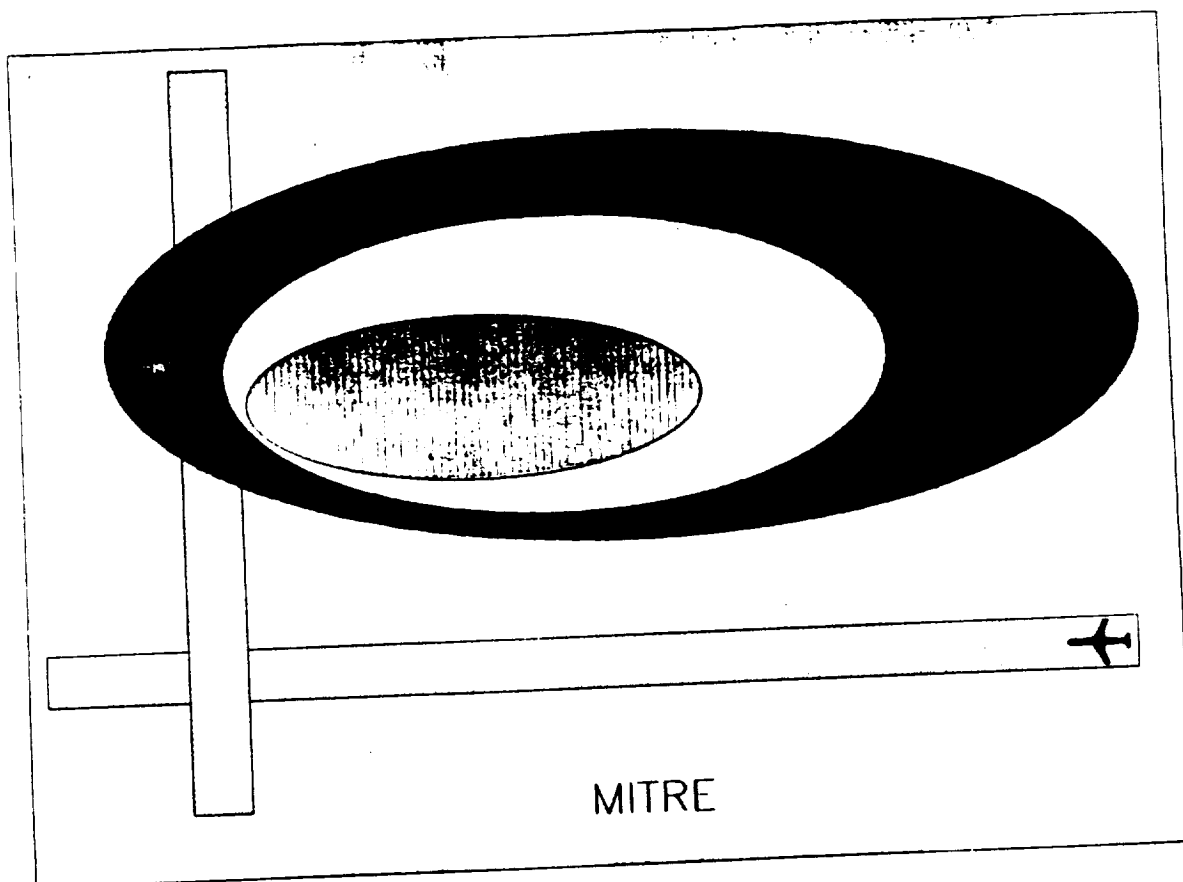
In addition, the movement of the boundaries of the pool yield a measure of shear, microburst strength, or the so-called maximum expected loss across the microburst. The depth of the change will also give a measure of the change, much like the relation given by Proctor of δv (m/s) = $2.5 \delta T^\circ\text{C}$.



Cross-sectional view of wind speed threshold sensor.

The sensor-transmitters (Senstrans) in the array have wind speed sensors similar to the Bedard-Fujita design shown, but modified by MITRE to include direction sensors, which are straingauges mounted directly on the rod which holds the Bernoulli sphere. When the ball moves, the direction is measured by resistance changes in the strain gauges. In the MITRE design, the pressure switch is replaced by a solid state pressure transducer soldered to the printed circuit board (PCB). The wind shear is then potentially obtainable in three ways, direct measurement, inference from the temperature depression, and geometrically, from the rate of expansion of the pool of new air.

Further, total pressure change, defined as the sum of the scalar pressure change and the dynamic pressure computed from the kinetic energy of the moving air, gives yet a third potential indicator of the presence of a microburst (Fujita). Changes in the static pressure over short periods of time (infrasound) have been postulated by Bedard as indicators of the presence of microbursts, but are not a possible output from the Senstrans array.



The plan for the operational air traffic controller (ATC) display is for a simple nested family of non-overlapping threat-indicating ellipses. Ellipses are very simply defined: five bytes completely describe the location and size of an ellipse. Therefore sixteen bytes completely describe three ellipses, since only one byte is needed for color. Given this economy of information to be transferred, the inner ellipse would be filled with red, indicating the highest threat, probably impenetrable by any aircraft on landing or departure. The area between that and the next ellipse, which totally surrounds the former, would be amber, indicating considerable threat, but possibly successfully penetrable by a microburst-experienced pilot. The finally enclosed area would be green indicating a moderate threat, but penetrable by all pilots except those who have no wind shear training. There would be no confusing overlapping of ellipses. However, there might be a small number of red ellipses within one amber ellipse, and there might similarly be multiple amber ellipses within one green ellipse. However, for transmission to fight decks, a simpler, three nested ellipse family for any one airport would be generated from the available data.

The advantage of ellipses is that they simplify the overly-complex shape of meteorological iso-lines or contours (such as radar echoes) which describe random noise phenomena and are not meaningful in detail. Where threats are defined, however, the selected ellipse is guaranteed to be the smallest ellipse which contains the defined threat, and does not overlap any inner ellipse.

Sixteen bytes of data can be transmitted in one information packet of Mode S data. In addition, at the low transmission rate of 1200 baud, 16 bytes of data can be transmitted anywhere in the world in a tenth of a second. Thus, the functional information of the location and size of a microburst on an airport can be transmitted in graphical form more economically than the ASCII format of the current controller verbal transmissions.

On the flight deck a color display of threats should facilitate pilot intentions, and an appropriate choice. In addition, a smart flight-deck computer could generate a probability of survival number between zero and 1 (1 being survival, 0 being impact) since it contains the aircraft configuration information.

Senstrans - Field Equipment

- Sensors and their sensitivities
 - Temperature sensor: 0.1deg C in 7 s; shelter air limits rate.
 - Pressure sensor: 0.1 mb, no time limit.
 - Will sense pressure changes ahead of descending air.
 - Allows estimate of temperature change due to pressure.
 - Wind speed sensor (Bedard-Fujita design, modified): 1 m/s above 5 m/s, no time limits.
 - Uses the same sensor as the pressure sensor.
 - Relative humidity sensor: 3% RH in 5 minutes.
 - Water content change will cause temperature change.
 - Sensor slow, but look-ahead and nowcasting possible.
 - Solar insolation
 - "Free": From output voltage of solar power supply.

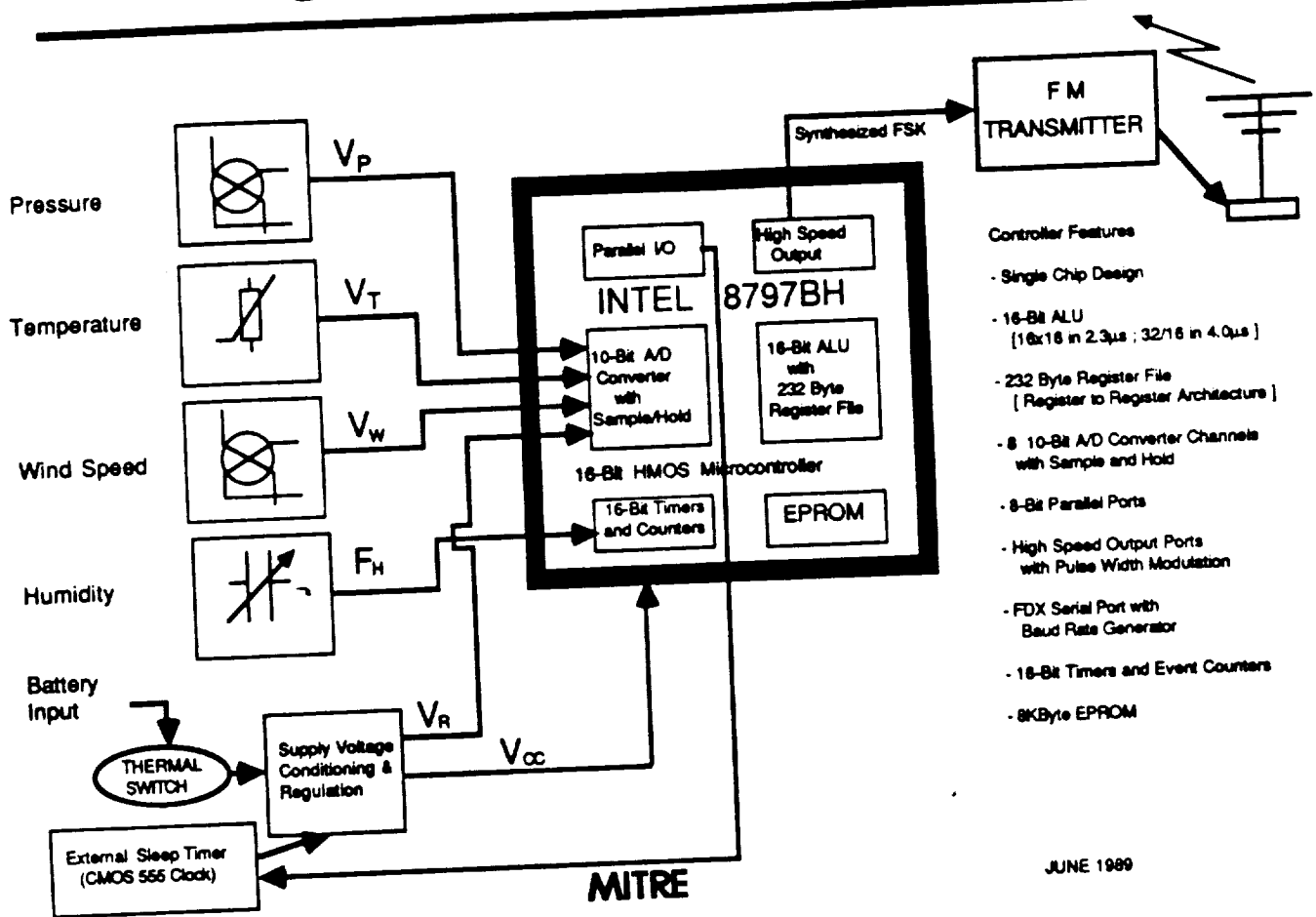
Adequate accuracy is achieved by accepting small lags in several parameters that are measured. Pressure and wind speed are available instantaneously, since they are measured on-chip by a sensor with a deflecting silicon membrane. Wind direction has similar qualities. Temperature has a slight lag because of the thermal mass of the sensor. Humidity, with a lag of the order of a minute, because of the need for water concentration change in a thin film, has the longest lag of the vital parameters.

Accuracies and lags are given in the following table:

Parameter	Sensor	Accuracy	Lag	Comment
Temperature	Thermistor	.1°C	7 seconds	
Differential	Silicon wafer	.1 millibar	zero	wrt Pressure
Wind Speed	Silicon wafer	1 m/s	zero	Above 5m/s
Relative Humidity	Thin film	3%	5 minutes	
Insolation	Solar array		zero	Accuracy N/A

Generally the sensors, the microcontroller, the transmitter are soldered on one two-sided PCB, thus eliminating many cables and connectors which are the most troublesome portion of complex equipment. This is mounted inside a standard instrument shelter which yields adequate exposure to the components within it. However, the solar panel, the battery, and the wind sensor must be elsewhere, so standard telephone cables with their gold-plated and sprung connectors are used where connectors are required.

SENSTRAN DESIGN

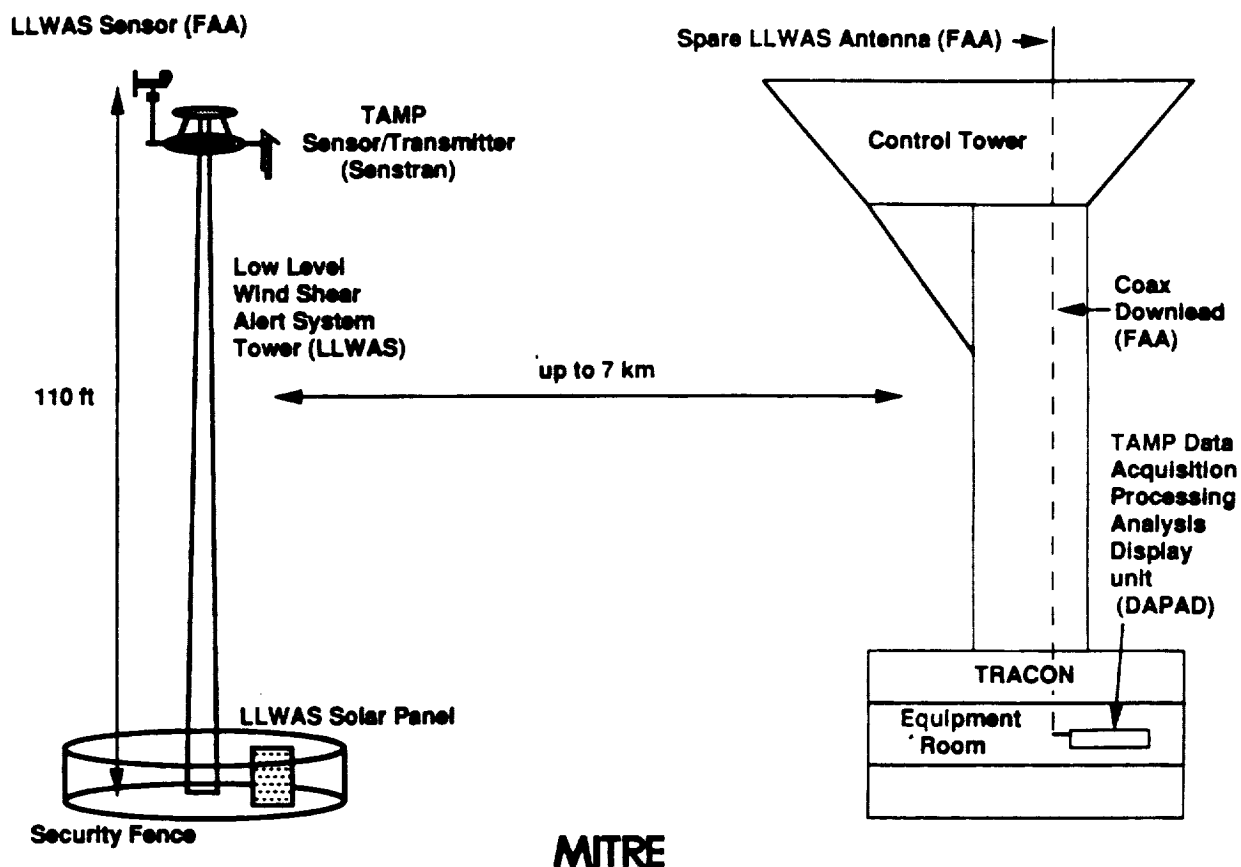


The microcontroller contains an A/D converter and has eight multiplexed analog inputs. These include one digital voltmeter which can be attached to any point on the PCB, and reads remotely. It feeds synthesized frequency shift keyed (FSK) tones to a 2.0 watt FM transmitter.

Unfortunately, the microcontroller also contains a fatal flaw which will not be addressed nor corrected by the manufacturer. Accordingly, many Senstrans exhibit "graceful failure", a tendency towards sparser transmission, and incorrect results. This could be detected and corrected by occasional visits to the various Senstrans. While this is not common to all microcontrollers, its unadvertised presence in the chosen chip was discovered too late to alter the design to accommodate some other chip.

Future Senstrans will be designed around permanently energized low-current microcontrollers to simplify design and to circumvent a similar fatal flaw should it be present in any of the low-current microcontrollers.

TAMP Installation at Stapleton

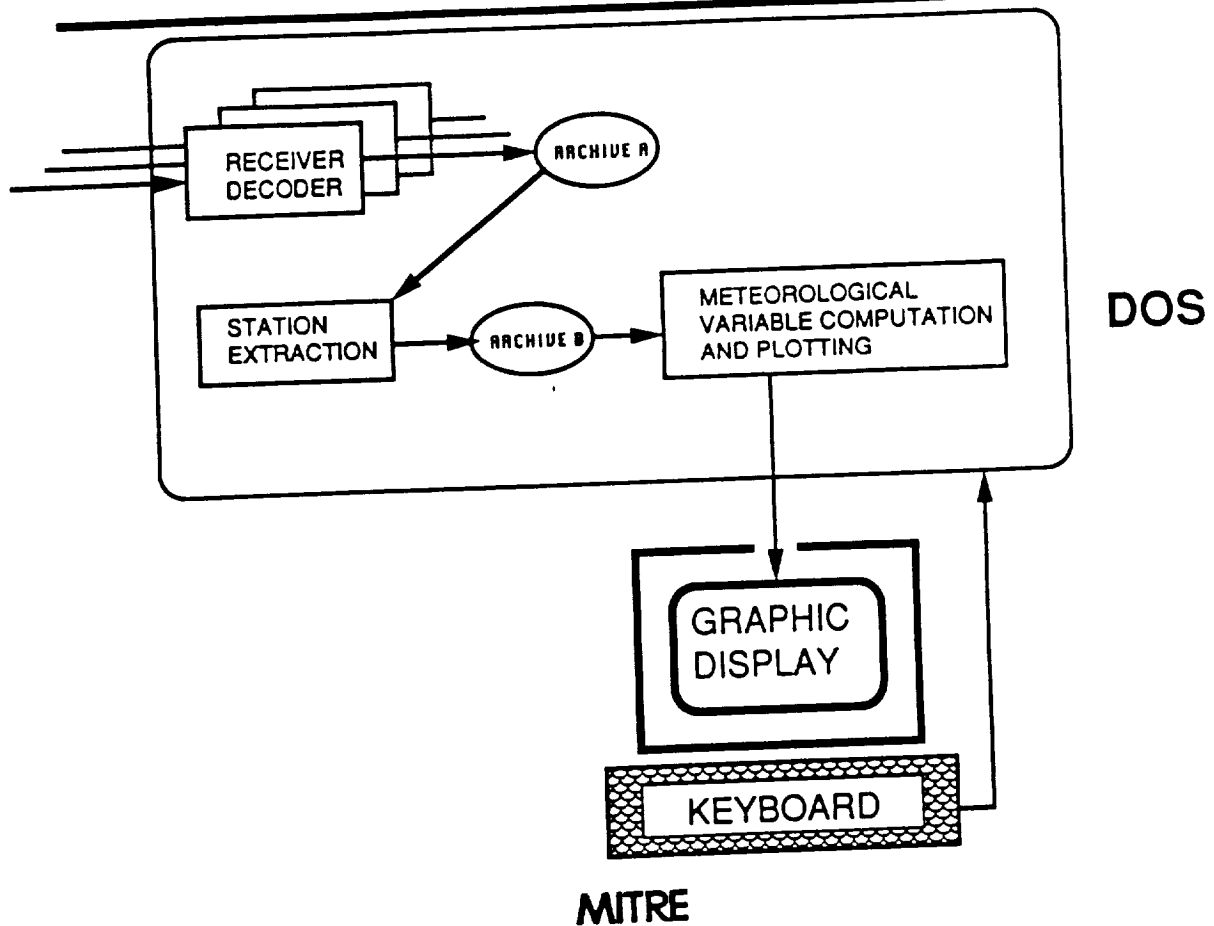


The receiving antenna is a spare LLWAS antenna on the roof of the ATC Tower, which feeds a receiver in the FAA equipment room. This is connected to a standard communications port on a PC via a 1200 baud demodulator. The decoding and archiving software is a Basic program.

With permission of the Stapleton Facilities Section, each of thirteen Senstrans is mounted on an LLWAS tower within a few feet of the operational LLWAS unit, and is up to 7 km from the receiver in the ATCT. It has no impact on the operation of LLWAS.

Operation was achieved on June 26, 1990 and continues.

DAPAD Software



The software within the data acquisition processing analysis and display unit (a PC) is a simple Basic language program. The archive is initially the hard-drive in the PC. Files are occasionally written to 3.5" floppy disks and are then sent to MITRE.

Results

One comparison has been made with the 11 August 1990 microburst. At this time there were only three remaining operational Senstrans, but its presence was detected by all of them.

Acknowledgments

The author is particularly grateful for the collaboration of the North West Mountain Region FAA, specifically the Denver Hub Airport Facilities Sector led by Mr. Jack McCormick.

Session VI. Heavy Rain Aerodynamics

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Session VI. Heavy Rain Aerodynamics

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Status of Heavy Rain Tests
Gaudy Bezos, NASA Langley

A STATUS REPORT

ON THE

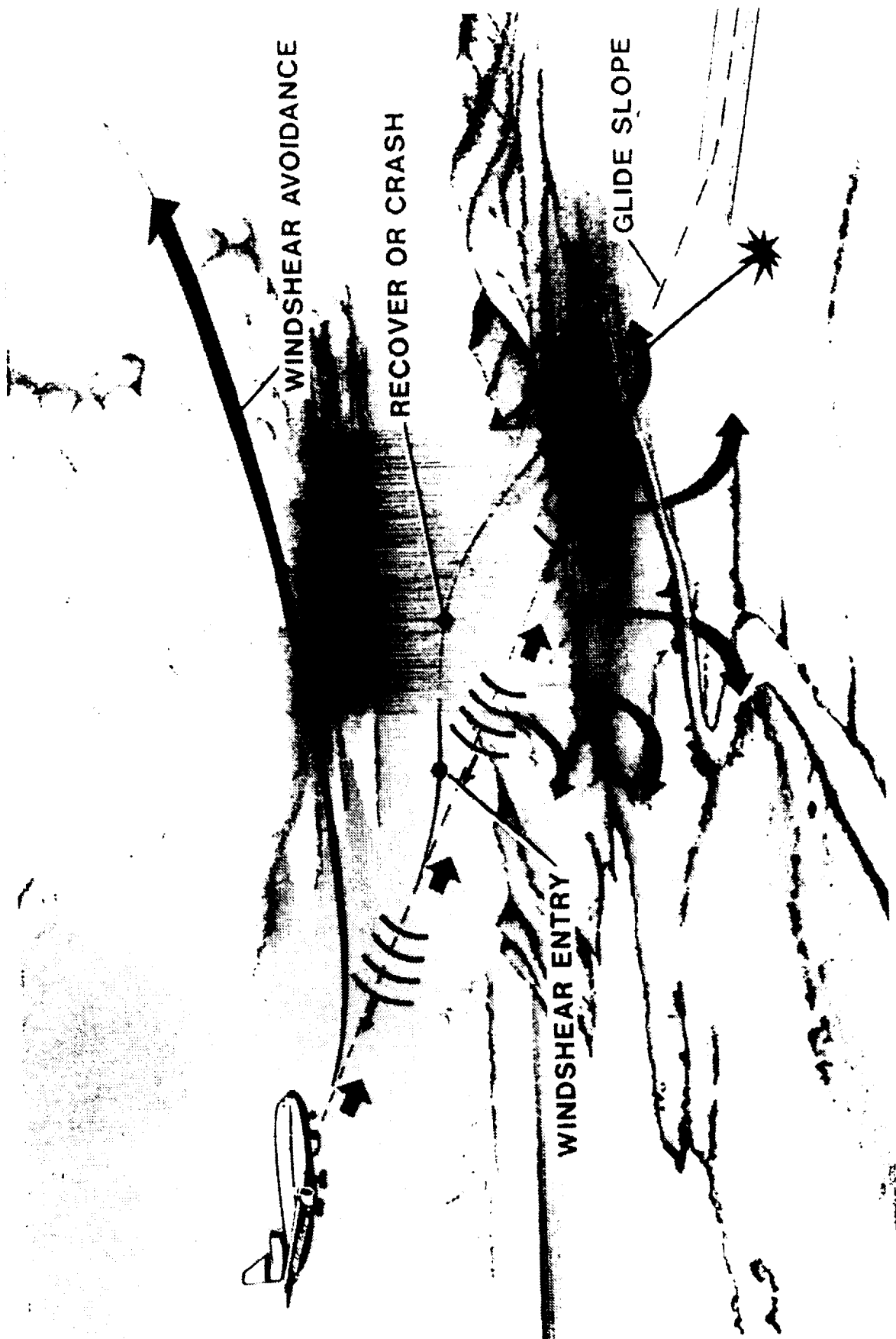
HEAVY RAIN EFFECTS PROGRAM

BY

GAUDY M. BEZOS

BRYAN A. CAMPBELL

NASA Langley Research Center
Subsonic Aerodynamics Branch
Applied Aerodynamics Division



AVIATION SAFETY CONCERN: RAIN

CHARACTERISTICS:

- **Highly-concentrated**
- **Short-duration**

WHY:

- **Windshear and severe rain partners**
- **10 out of 25 windshear accidents occurred in a rain environment**
- **5 out of 10, severe rainstorm present**

THE HEAVY RAIN EFFECTS PROGRAM

OBJECTIVES:

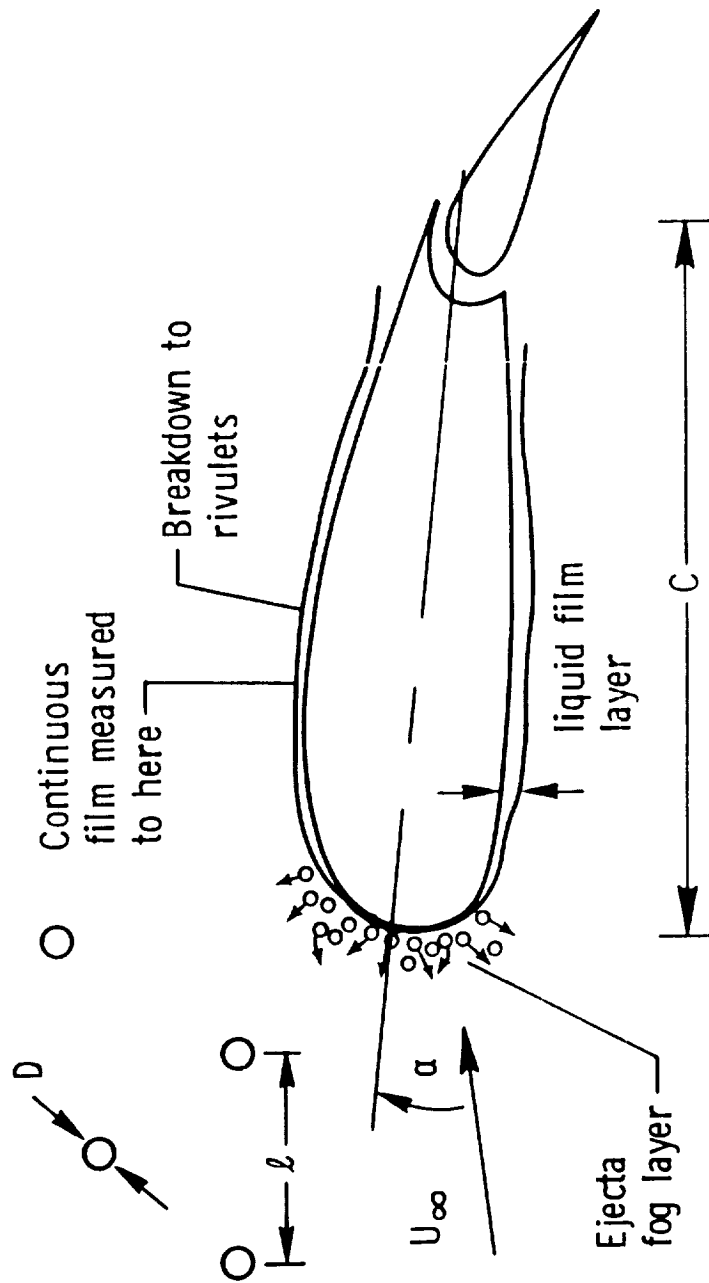
To Determine:

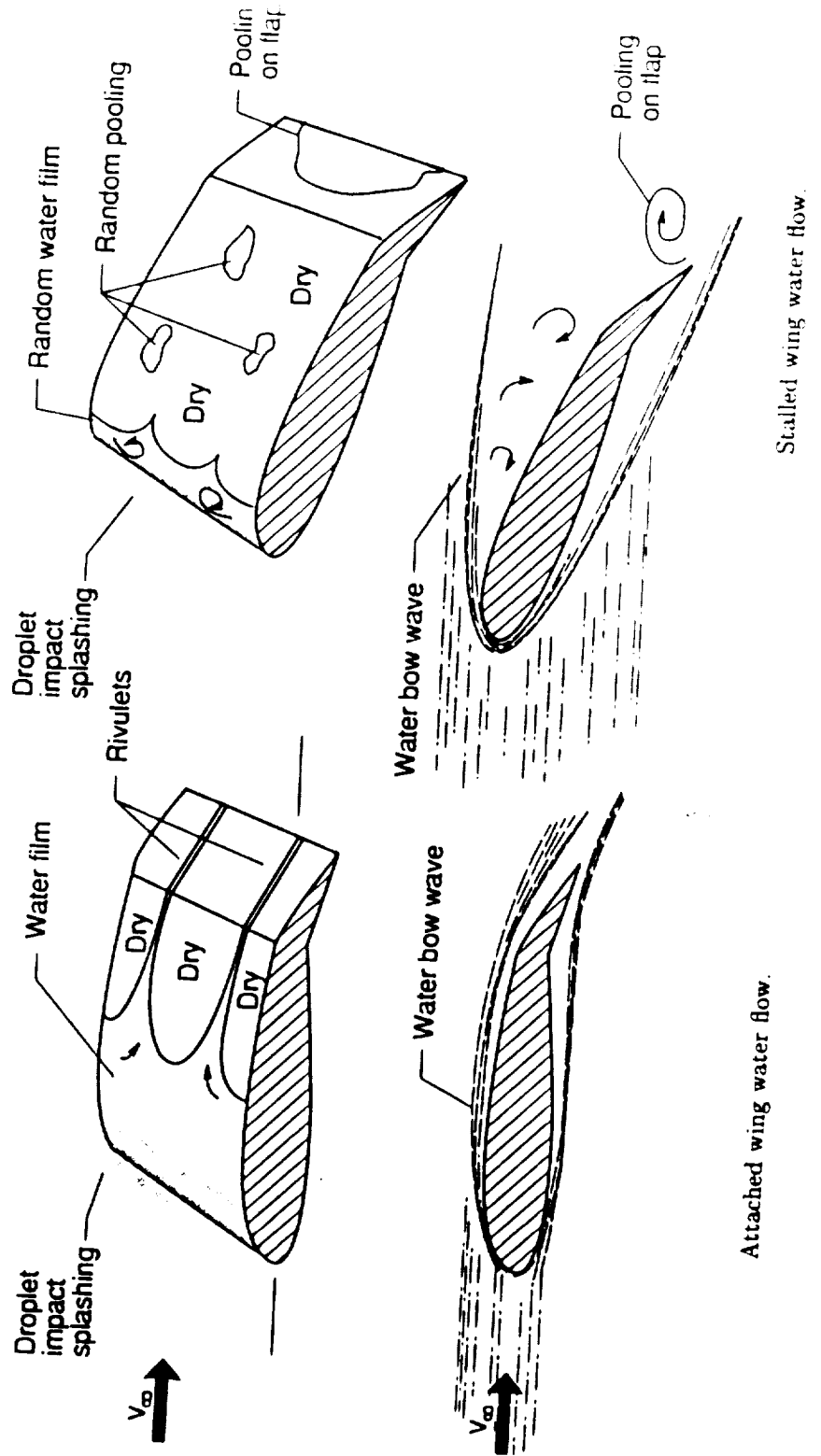
- **The effect of rain on aircraft performance**
- **The consequences of the effect during a microburst encounter**

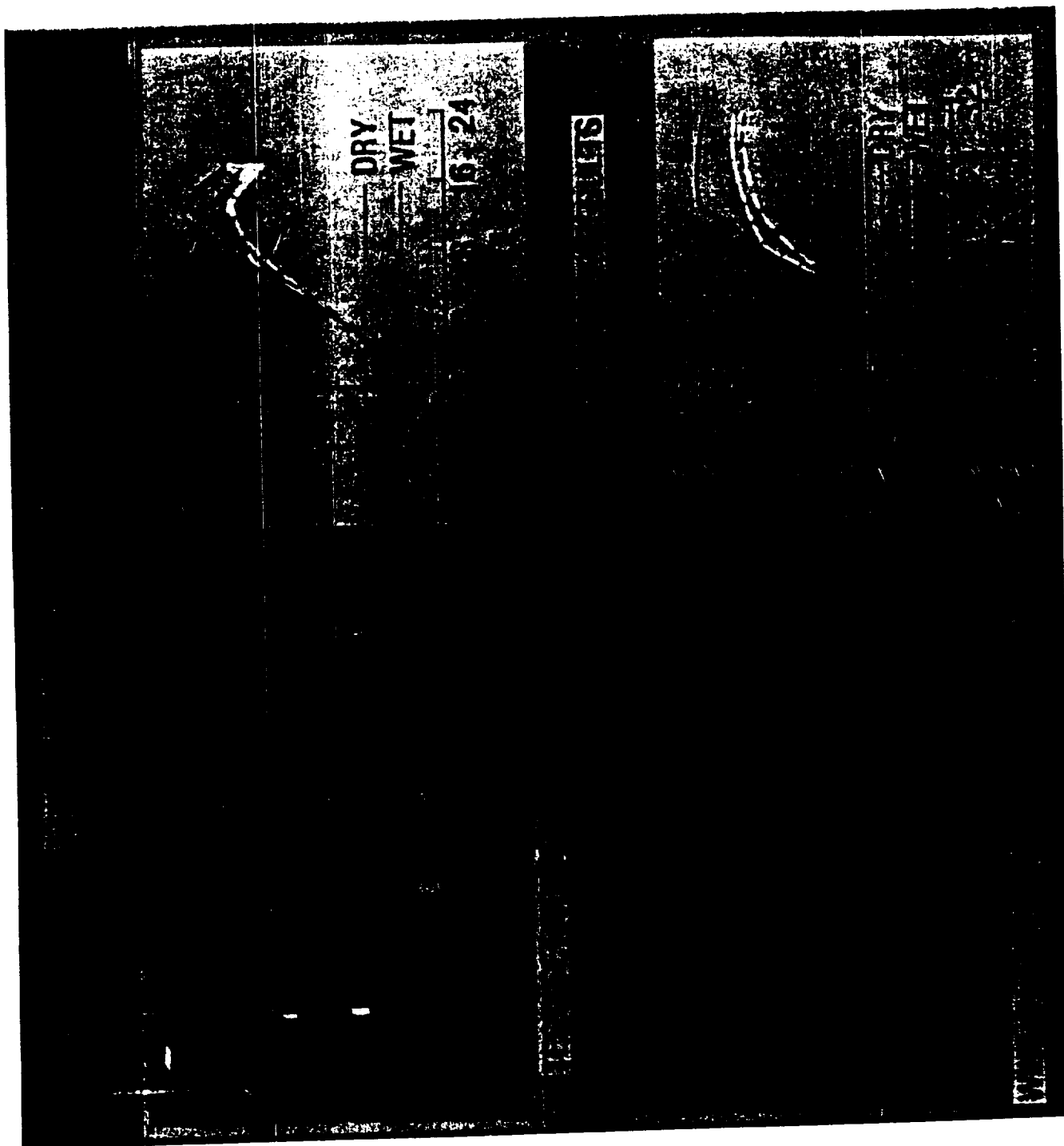
OVERVIEW

- Two-phase flow dynamics
- Wind tunnel results
- Issues
- Large-scale results
- Future plans
- Summary remarks

RAINDROPS INTERACTING WITH AN AIRFOIL





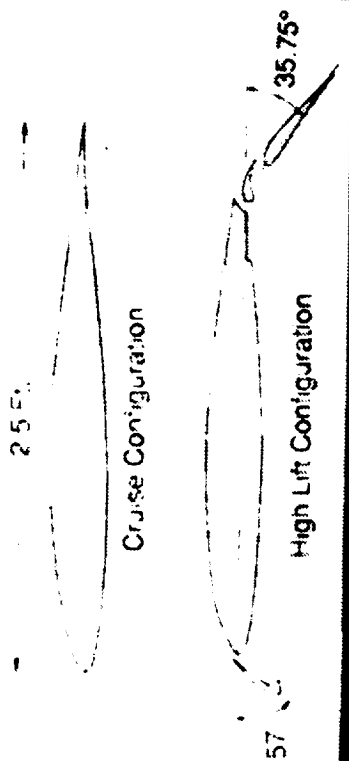


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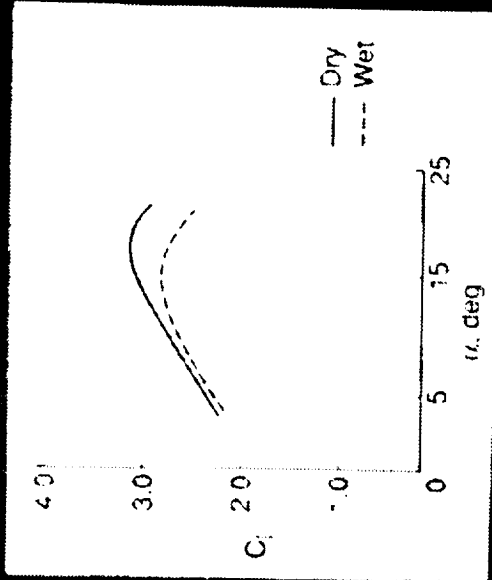
Rain Effects on Airfoil Performance

Cross Section of the Wing Model

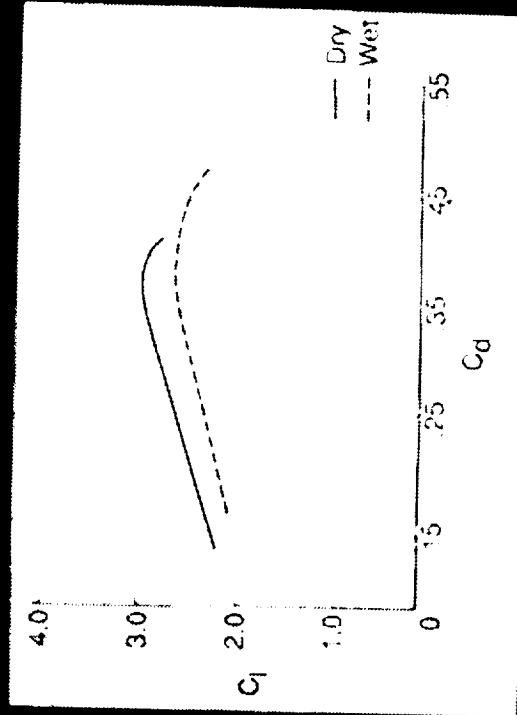
NACA 64-210 AIRFOIL



High Lift Configuration



Test Set-up in 14 by 22 Foot Tunnel with Simulated Rain



WIND TUNNEL TEST RESULTS (1982-1988)

- Rain has an effect on airfoil performance
- Rain affects:
 - Maximum lift capability
 - Stall angle of attack
 - Drag
- Magnitude of the effect is dependent on:
 - Rainfall rate
 - Airfoil geometry
 - Slat/flap deflection

ISSUES

- **The scaling of the small-scale results to full-scale aircraft**
- **The accurate simulation of natural rain**
- **The acquisition of:**

Natural rain data, i.e.:

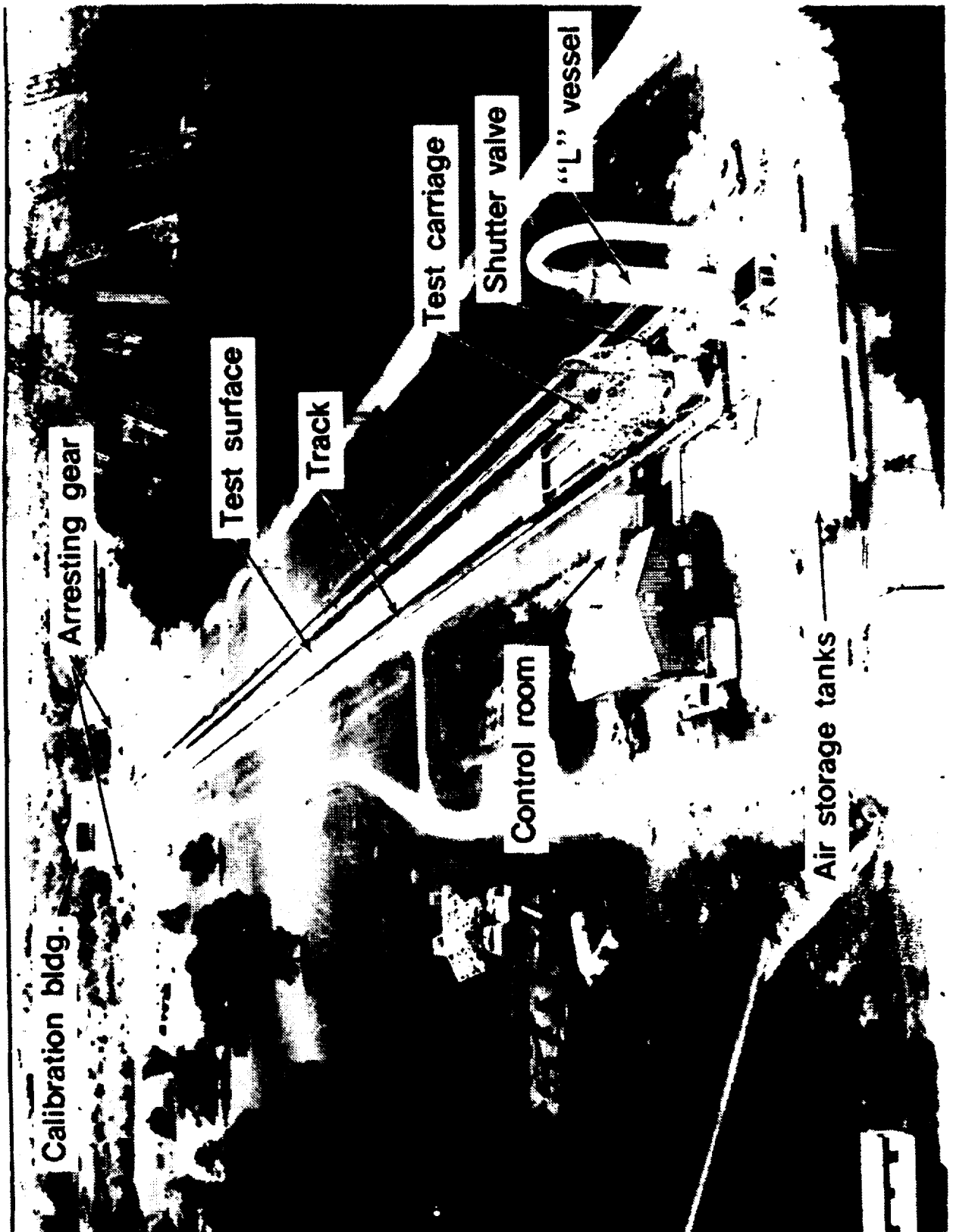
- **Rainfall Rate**
- **Probability of a Rain Event**
- **Droplet Size and Distribution**

Droplet impacting dynamics data

NASA

1-85-12 (00)

AIRCRAFT LANDING DYNAMICS FACILITY



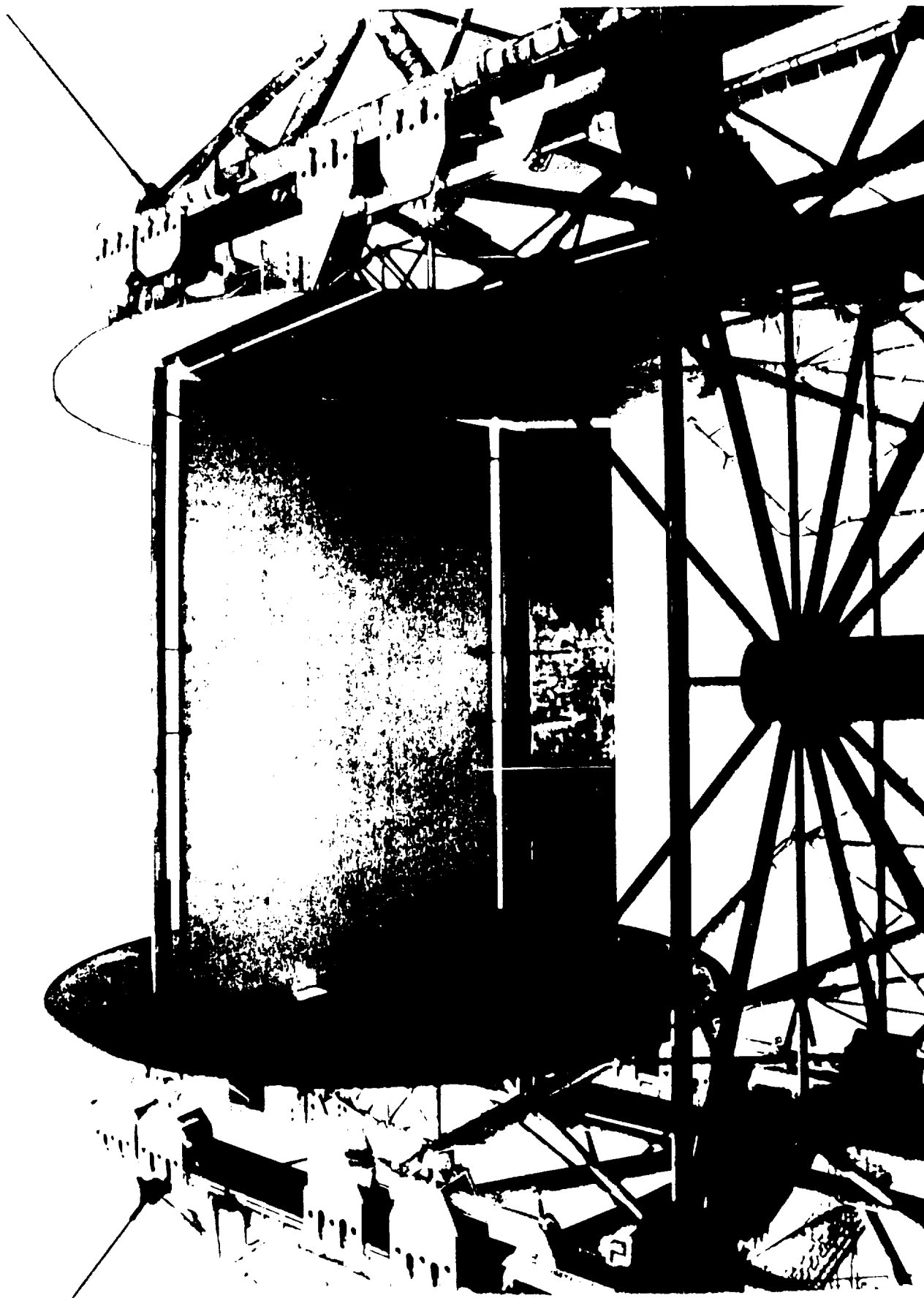
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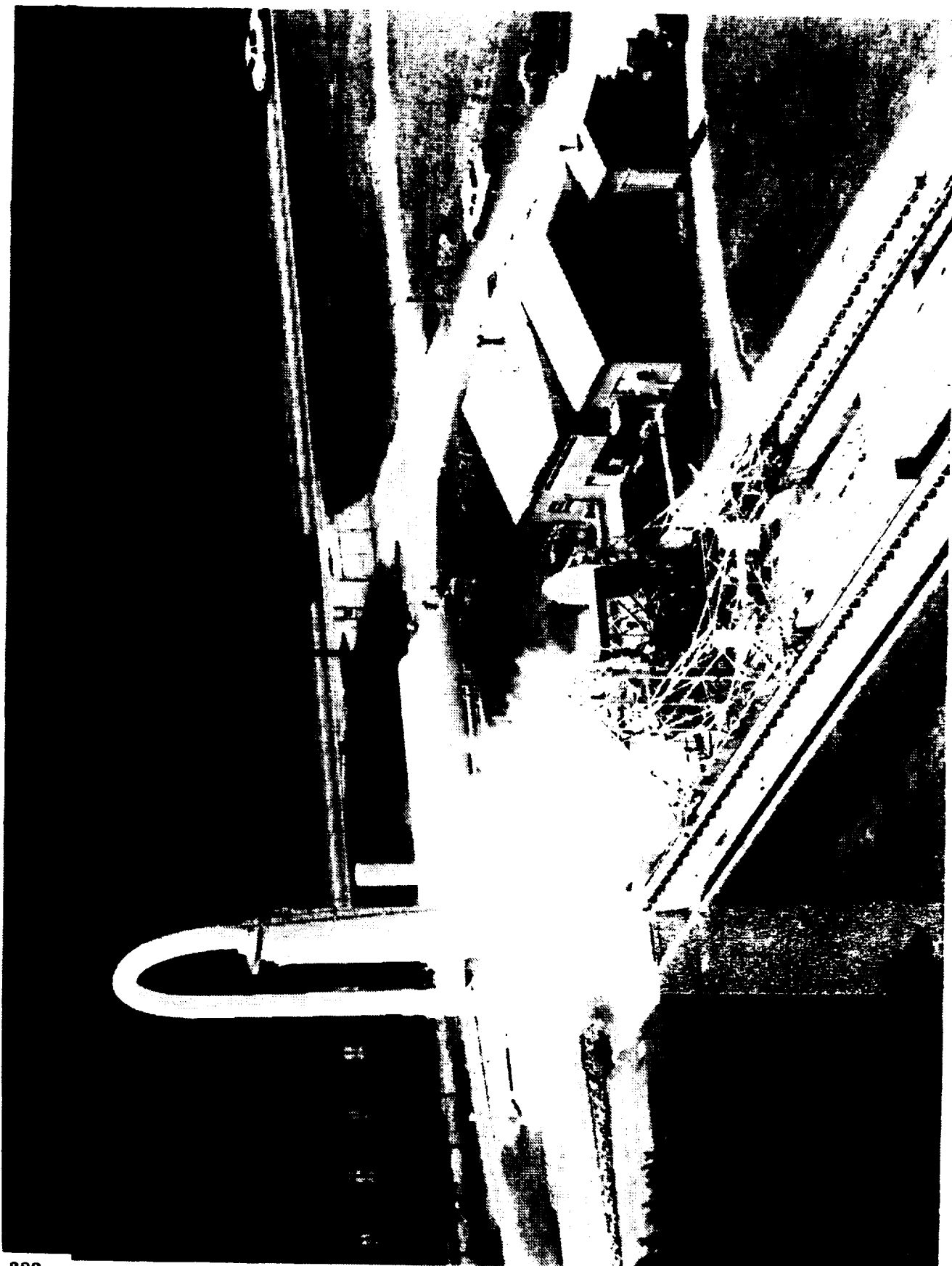
NASA



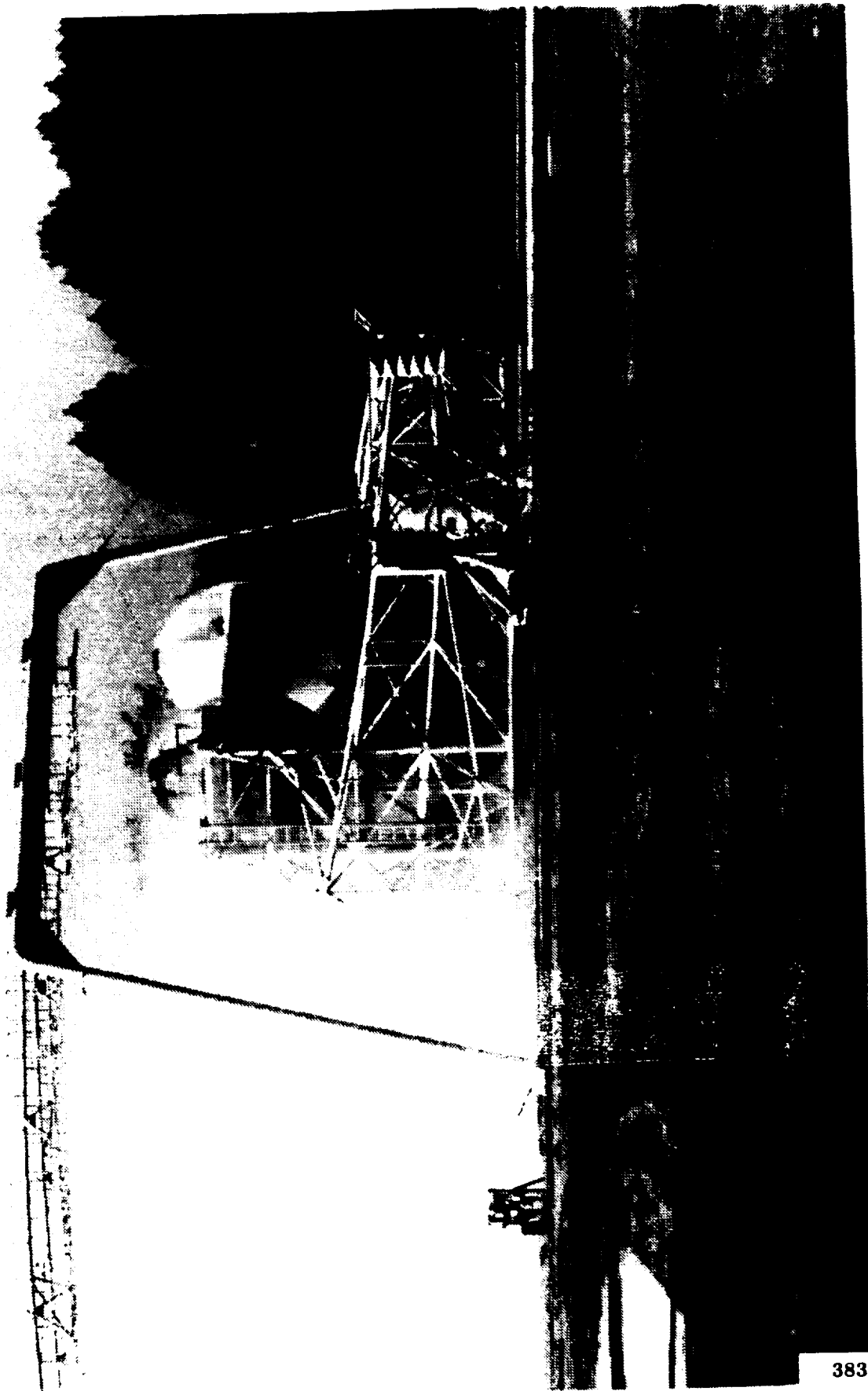
NSA



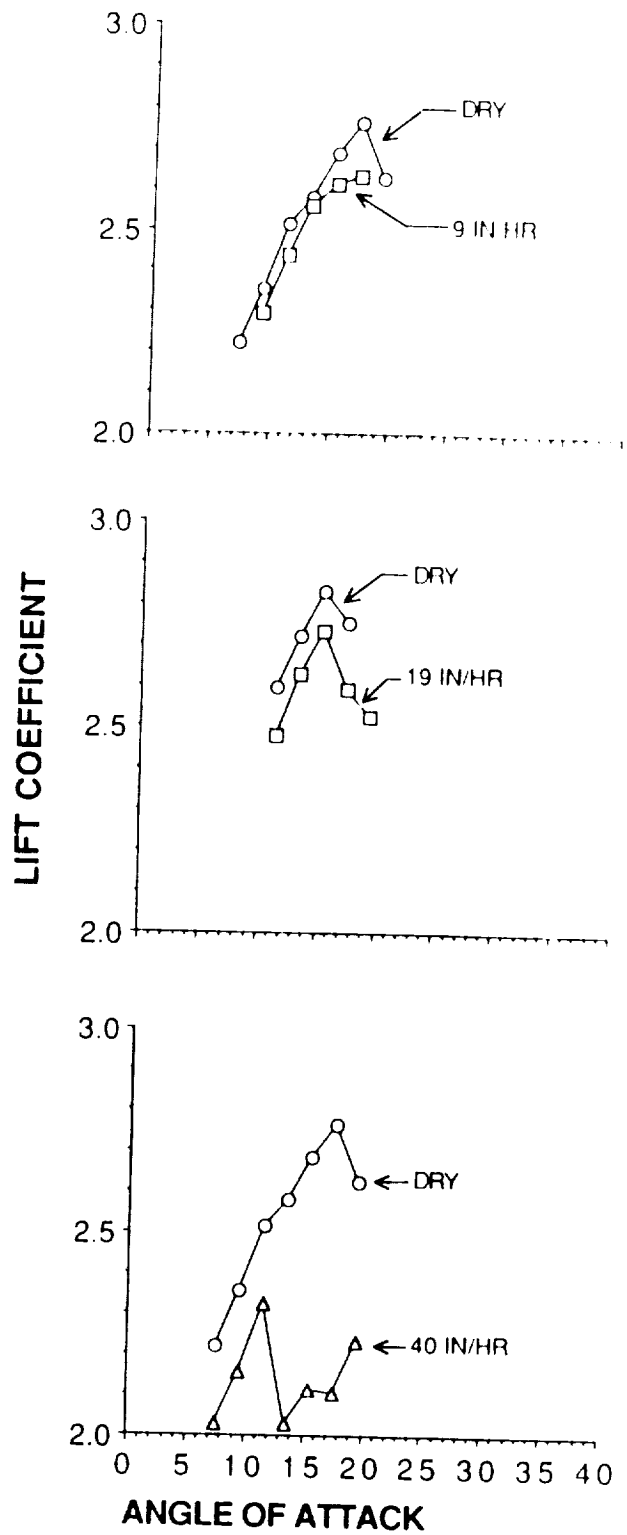
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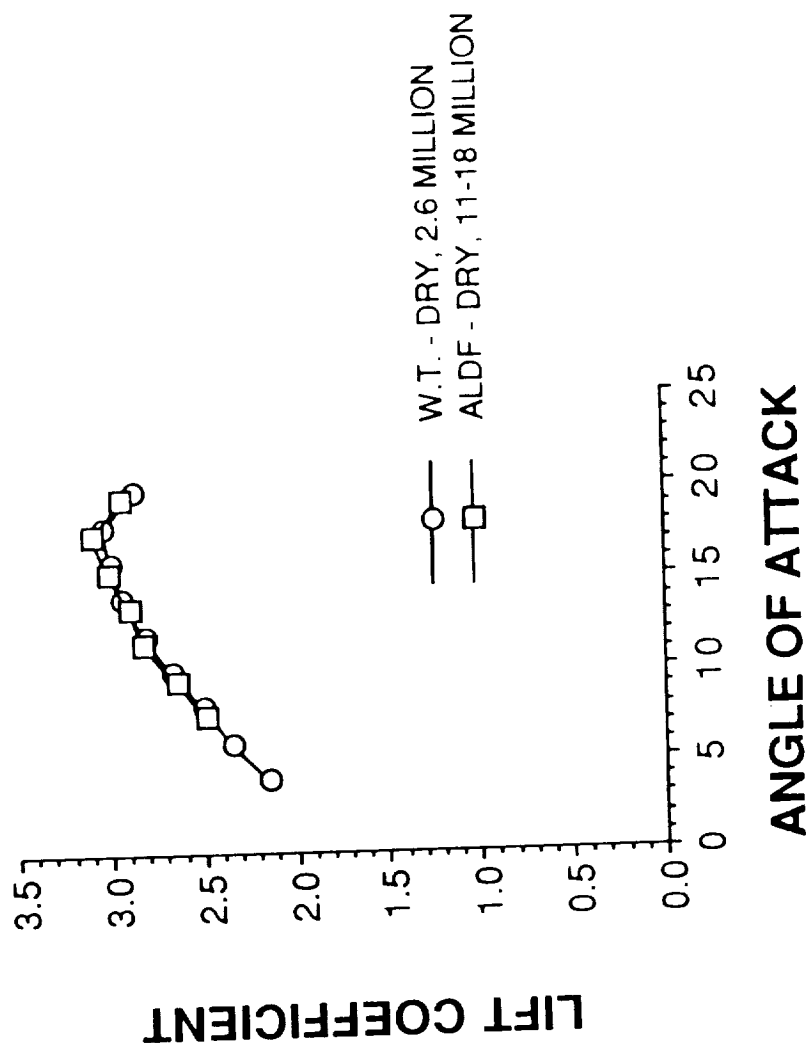
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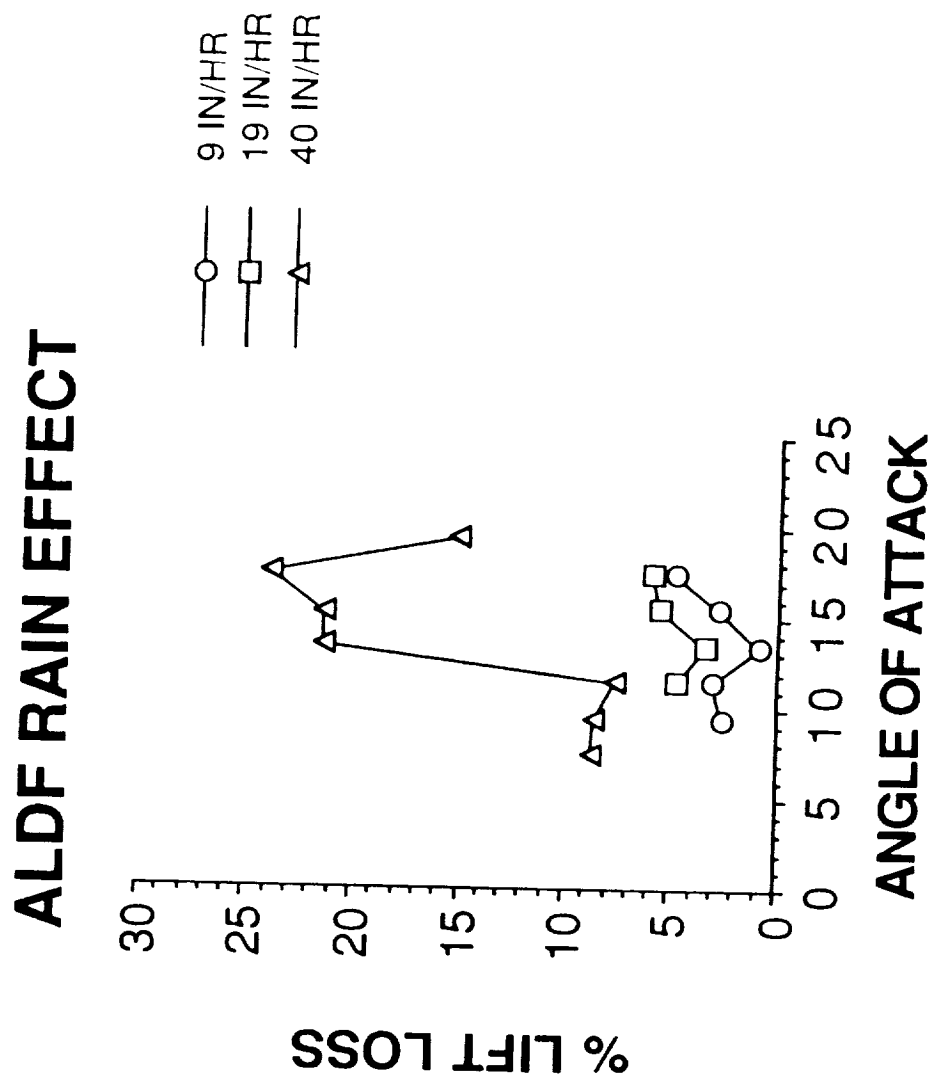


ALDF HIGH-LIFT DATA

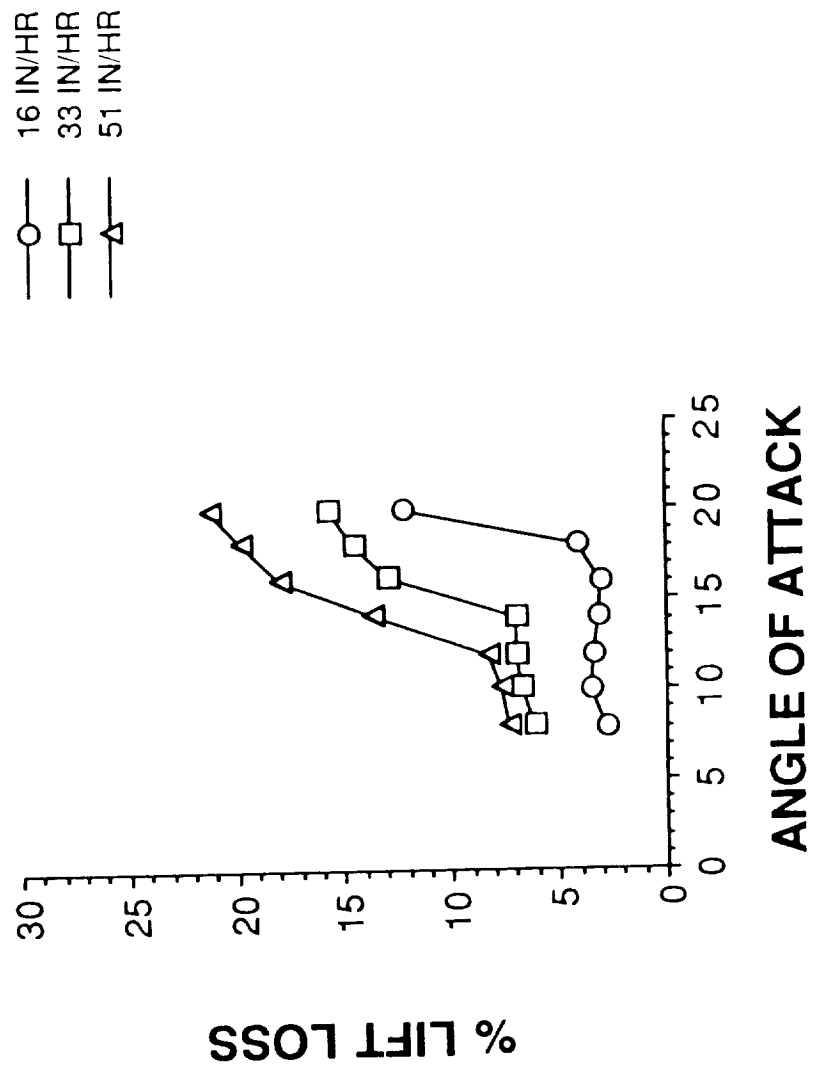


REYNOLDS NUMBER EFFECT



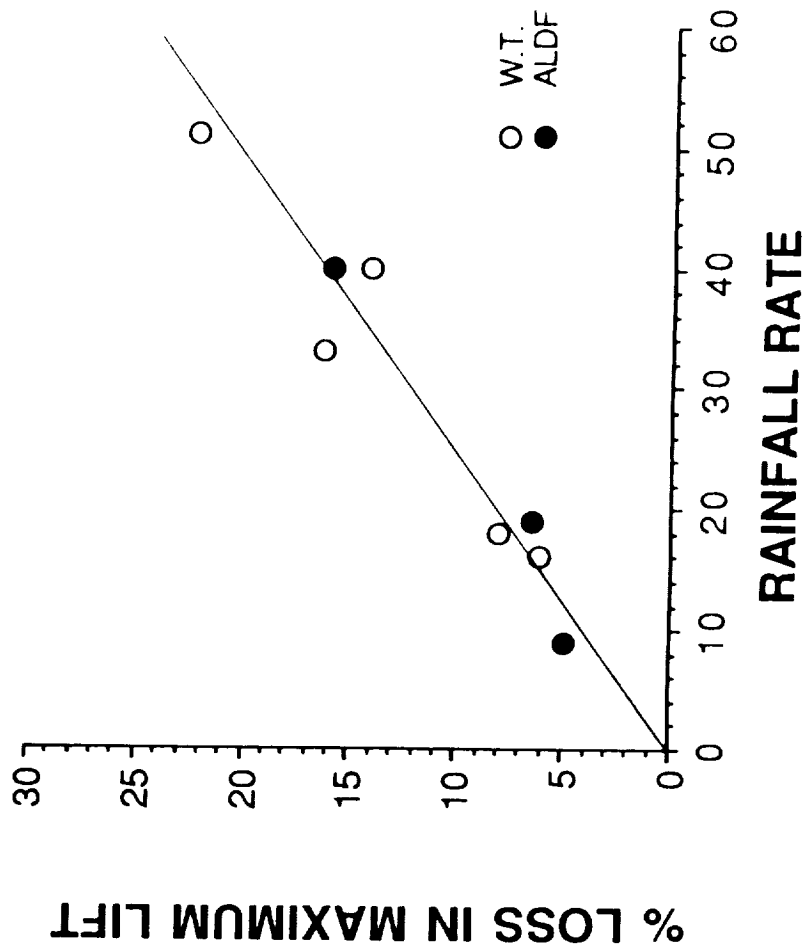


WIND TUNNEL RAIN EFFECT

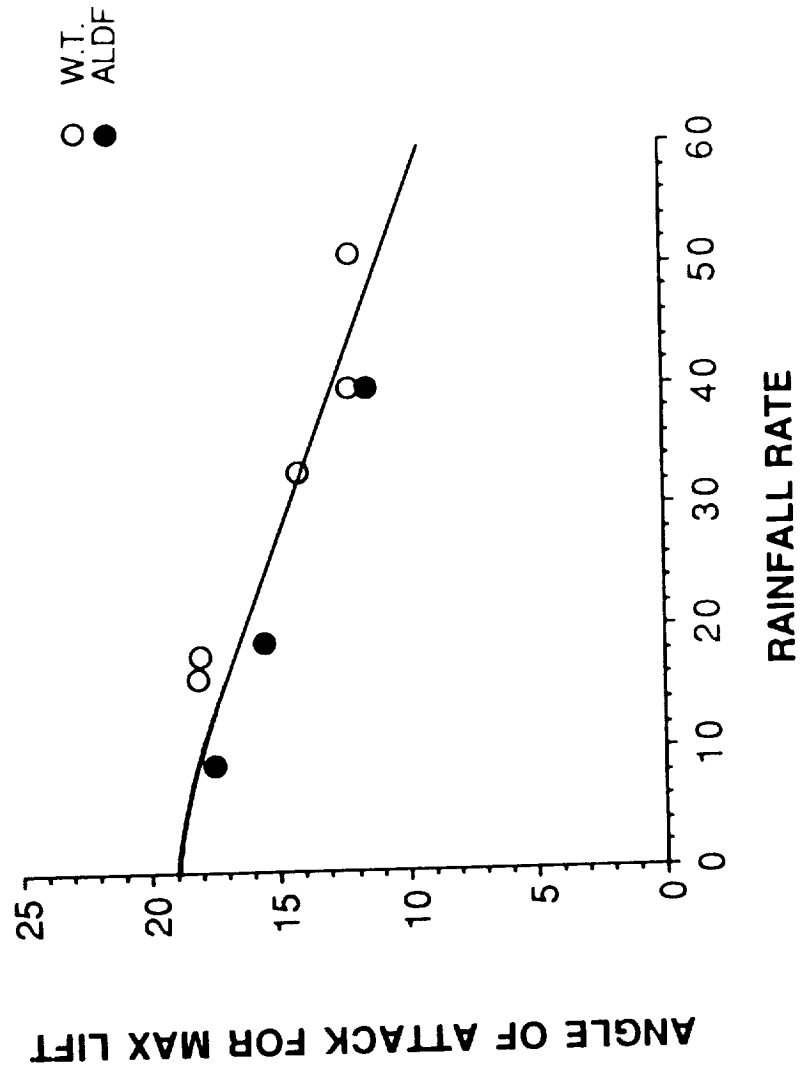


C-5

RAIN EFFECT ON MAXIMUM LIFT CAPABILITY



RAIN EFFECT ON STALL ANGLE OF ATTACK



FUTURE PLANS

- **Complete new wind tunnel rain spray system**
- **Conduct wind tunnel tests on 2D-section and full configuration models**
- **Obtain further insights into two-phase flow dynamics**

SUMMARY REMARKS

- Large-scale data acquired at three rainfall rates
- Established similar trends between ALDF and the wind tunnel
- Plan to acquire full configuration data in the 14- by 22-Foot Subsonic Tunnel

Status of Heavy Rain Tests - Questions and Answers

Q: RICHARD DUBINSKY (Sky Council) - What influence and/or relationships do you expect for extreme ranges of drop size distributions in heavy rain for microburst and shears, etc.?

A: GAUDY BEZOS (NASA Langley) - I'm not familiar with the drop size distributions that have been measured inside wind shear environments of severe thunderstorms. If there is data available it's a very small data base. I can only share with you my experiences in trying to form droplets in a wind tunnel and at the ALDF facility. In the wind tunnel environment, we've noticed that the difference between the exit velocity of the water from the nozzle and the free-stream velocity we wanted to accelerate the drops to, made a great difference in the shape and size of the drops themselves. Anything larger than 2 mm in size would actually shatter and form much smaller drops. So the wind tunnel test technique gave us an average drop size of about 1.5 mm. At ALDF we used commercial nozzles. The spec sheet on those nozzles says that they produce drops from as small as 1/2 mm in size to 4 mm in size. It's very difficult to measure drops in an outdoor facility. We used a sort of a shadow-graph technique. We had a little box with a lens, a camera and a slit in the top. We let the drops fall through the slit and would take a picture of it. By just looking qualitatively at what kind of distribution we got, we did see 1/2 mm size drops and we did see 4 mm size drops and everything in between. The ALDF facility rain system was purposely designed to allow the droplets of all the different sizes to achieve their terminal velocity, + or - 10%, which even for the smallest size drops it would take 14 feet. So the drops did achieve the proper physics involved in forming and falling to the ground. I do know that if you are in a wind shear situation you'll have down drafts and that may entrap the rain that is there and actually force it down a lot harder and maybe the drops themselves will have a different characteristic. There is research, I don't remember the person's name, which looked at drop size distributions in light showers versus severe thundershowers and there is a different distribution.

Q: RICHARD DUBINSKY (Sky Council) - How will you generate and measure different rain drop size distributions for your future wind tunnel experiments?

A: GAUDY BEZOS (NASA Langley) - We'll generate the different drop sizes by varying the exit nozzle pressure. We are planning to put our rain system in the settling chamber of our wind tunnel which will minimize the difference between the air stream velocity and the exit velocity of the drops. We hope to be able to keep in tact the drops, the large size drops, like 4 mm in size. We plan to measure the drops using two techniques. We'll again use the shadow-graph photographic technique and we are also developing a laser system that will basically be an unobtrusive device which will allow the drops to cross the sheet of light and then determine its size and its velocity by the width of the interference as it crosses the laser beam.

Q: WALT OVEREND (Delta Airlines) - How, when you conducted rain tests did you overcome the water effect on your sensors or your sensor systems?

A: GAUDY BEZOS (NASA Langley) - The instrumentation that we used to acquire our aerodynamic data were strain gauge load cells and they were unaffected by the rain environment. They were waterproofed before hand. We were able to measure aerodynamic lift and the drag seen by the model without any problem. We also had an on board pitot static system on the carriage to give us true airspeed. That also did not show a difference in and out of the rain environment. But, you have to remember that we were only in the rain environment for 2 seconds so the probability of a drop hitting the pitot static

tube at just the right spot to clog it up is kind of unlikely. In the wind tunnel we tried to measure the static pressures on the wing surface and we found that we had great difficulties in doing that because the water would always clog up the line. So we couldn't measure the pressure on the surface of the wing.

Q: WALT OVEREND (Delta Airlines) - What do you see as a change in effect on a three dimensional wing, including tip vortices from your 2 dimensional testing?

A: GAUDY BEZOS (NASA Langley) - The first thing I would like to point out is that we have done some three dimensional testing on very simplistic models. The first one was on a NACA 0012 airfoil section with a generic fuselage and a simple flap. The other was on a NACA 23015 airfoil section model which also had a simple flap system on the trailing edge. The results do indicate there are lift losses and drag increases. The magnitude and the shape of these curves may differ a little bit but we don't expect to see many great changes in our 3-D testing in terms of those characteristics. One thing that we will probably see is an effect of the fuselage and the tail surfaces. We hope to do a section by section test of a full configuration model starting first with the swept wing by itself on a splitter plate, then test the fuselage and tail surfaces, and then put the whole system together to see if we can isolate which areas contribute to performance losses. I did want to point out that testing in a wind tunnel environment or at ALDF is not easy. There are a lot of operational difficulties involved. A wind tunnel wasn't made to have water thrown in it. All the instrumentation must be waterproofed. Our blades, which are wooden, have to be protected from the erosion of the water. We can't test in the wind tunnel during the winter months because whatever residual water is left in the tunnel circuitry actually forms into ice and then when we initially turn the system on it actually digs holes, pits, into the wooden blades. The wind tunnel is not the ideal test technique. It really is a lot of work and effort. At ALDF we've been testing for two years and we've got 36 data points. Now, of those 36 data points we have some repeat points, but it's a very slow process. We are always fighting nature, bad weather and high winds.

Session VI. Heavy Rain Aerodynamics

N91-24181

Heavy Rain Field Measurements
Ed Melson, NASA Wallops

HEAVY RAIN FIELD MEASUREMENTS

W. EDWARD MELSON, JR.

NASA/GODDARD SPACE FLIGHT CENTER/WALLOPS FLIGHT FACILITY

*THIRD COMBINED MANUFACTURERS' AND TECHNOLOGISTS'
AIRBORNE WIND SHEAR REVIEW MEETING
OCTOBER 16-18, 1990
HAMPTON, VIRGINIA*

HEAVY RAIN FIELD MEASUREMENTS

W. EDWARD MELSON, JR.

NASA/GODDARD SPACE FLIGHT CENTER/WALLOPS FLIGHT FACILITY

ABSTRACT

Tests have shown that the effects of heavy rain on the aerodynamic performance of a wing produces a degrading influence. These tests have also shown that the transition from steady-state dry condition of the wing to a steady-state wet condition takes place in a matter of seconds. This short transitional period led to a need for understanding short-duration high-intensity natural rainfall. The current data base of the National Weather Service for rainfall is averaged over relative long time constants. This averaging tends to mask the short-duration, high-intensity rainfall characteristics.

A weight-measuring rain gauge was developed to collect rain data and configured to operate at a high sample rate (one sample per second). Instead of averaging the rain rate in minutes, hours, and sometimes days as normally performed, the rain data collected are examined in seconds. The results of six field sites are compiled. Rain rate levels, duration of downpours, and frequency of heavy rainfall events are presented.

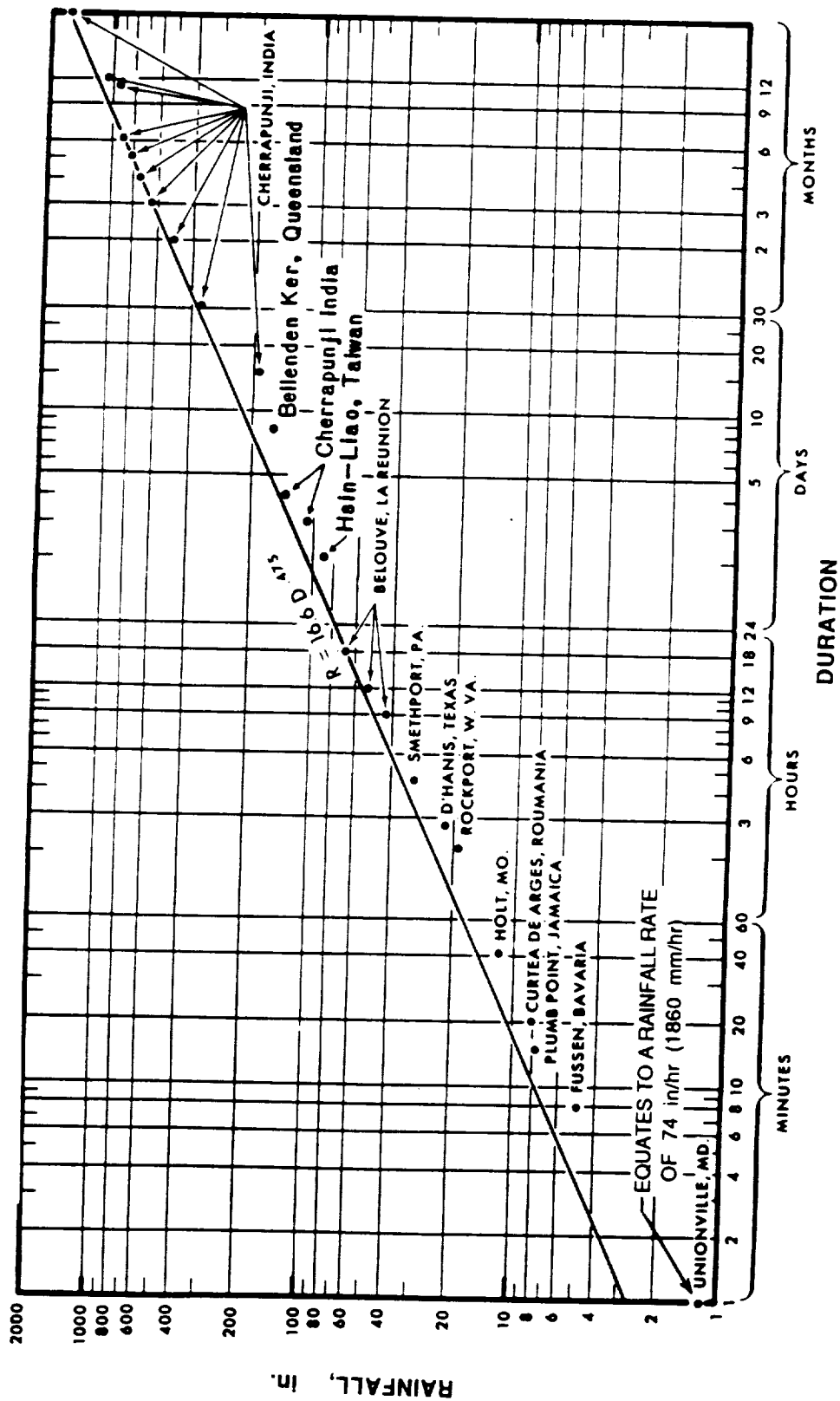
OUTLINE

- **HEAVY RAIN**
- **TRANSITION TIME**
- **RAINFALL MEASUREMENTS**
- **DATA REDUCTION**
- **HEAVY RAINFALL CHARACTERISTICS**

HEAVY RAIN HAS A DEGRADING INFLUENCE ON THE AERODYNAMIC PERFORMANCE OF A WING

- **WHAT IS HEAVY RAIN ?**
- **WHAT IS THE FREQUENCY OF HEAVY RAIN ?**

WORLD'S GREATEST OBSERVED POINT RAINFALLS



WMO, Probable Maximum Precipitation, 1986

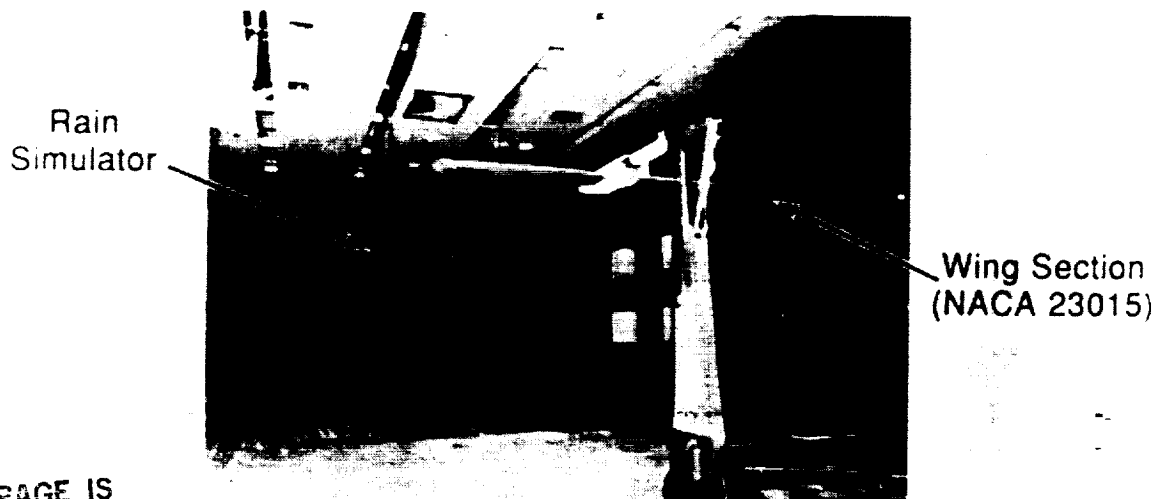
**TRANSITION OF THE WING'S PERFORMANCE FROM
A DRY TO A WET CONDITION TAKES PLACE IN**

SECONDS

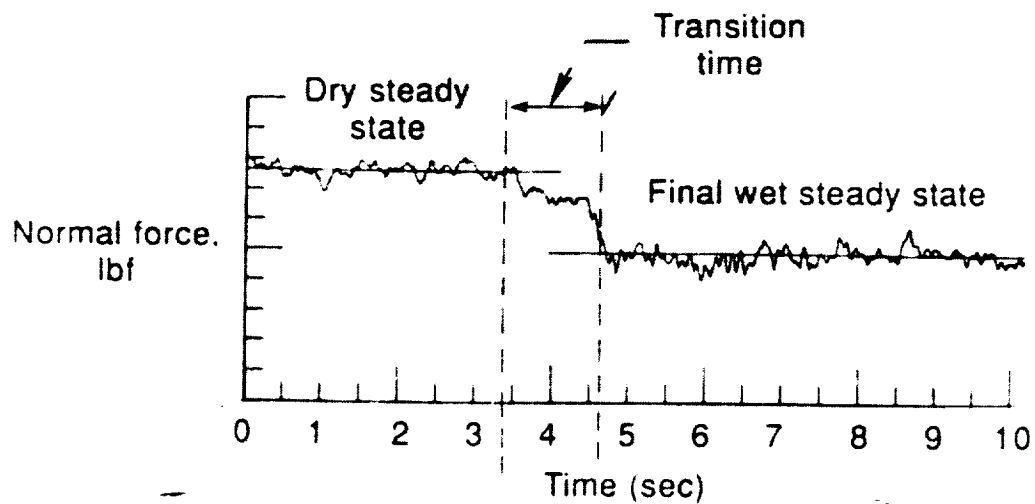
- **CURRENT RAINFALL DATA BASE IS AVERAGED OVER
RELATIVELY LONG TIME PERIODS (MINUTES, HOURS.)**
- **THIS PROCESS TENDS TO MASK THE SHORT-DURATION,
HIGH-INTENSITY RAINFALL CHARACTERISTICS**

DYNAMIC RESPONSE OF WING IN SIMULATED RAIN

Test set-up in 14-by-22 foot subsonic tunnel



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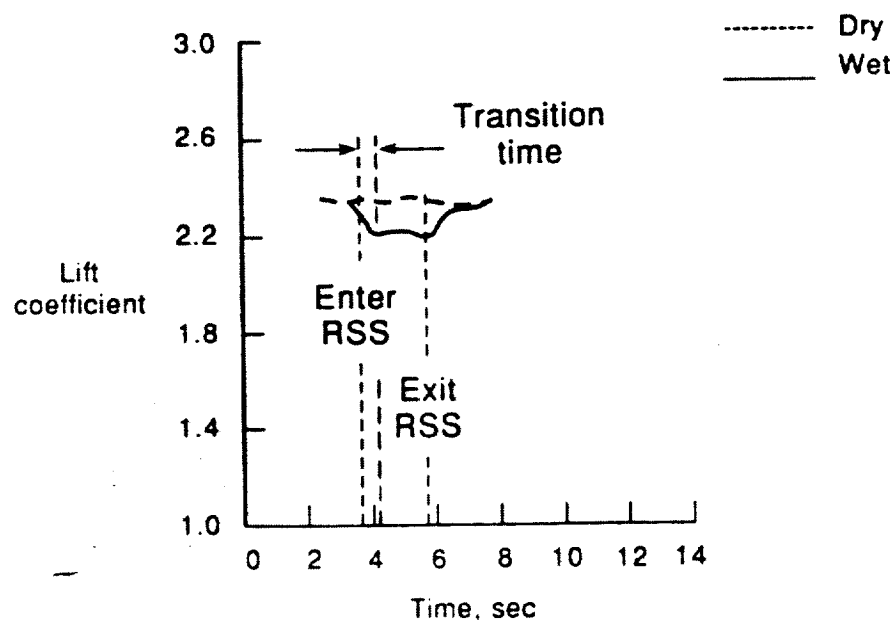
(Campbell & Bezos, 1969)

DYNAMIC RESPONSE OF WING IN SIMULATED RAIN

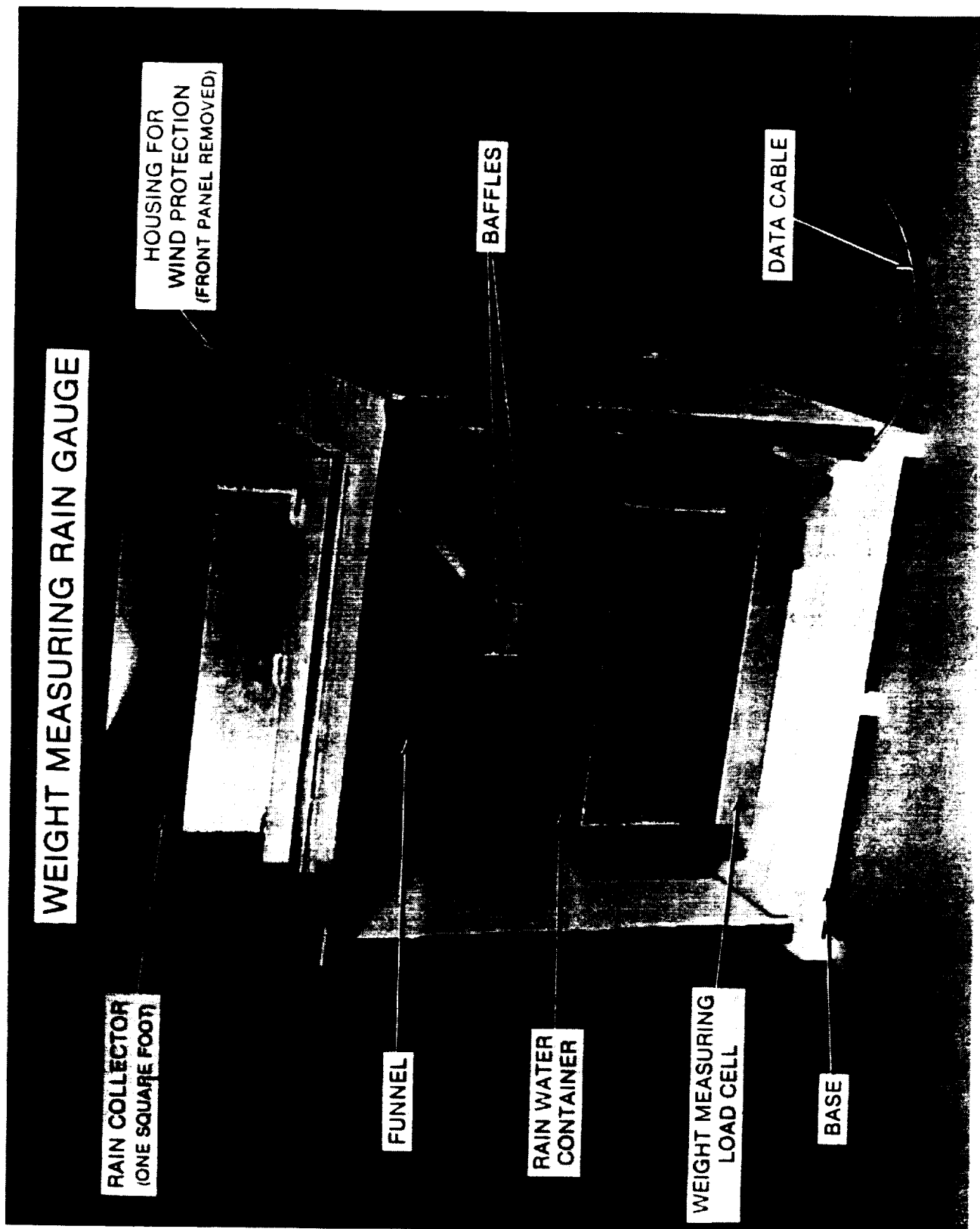
TEST SET-UP AT THE AIRCRAFT LANDING DYNAMICS FACILITY

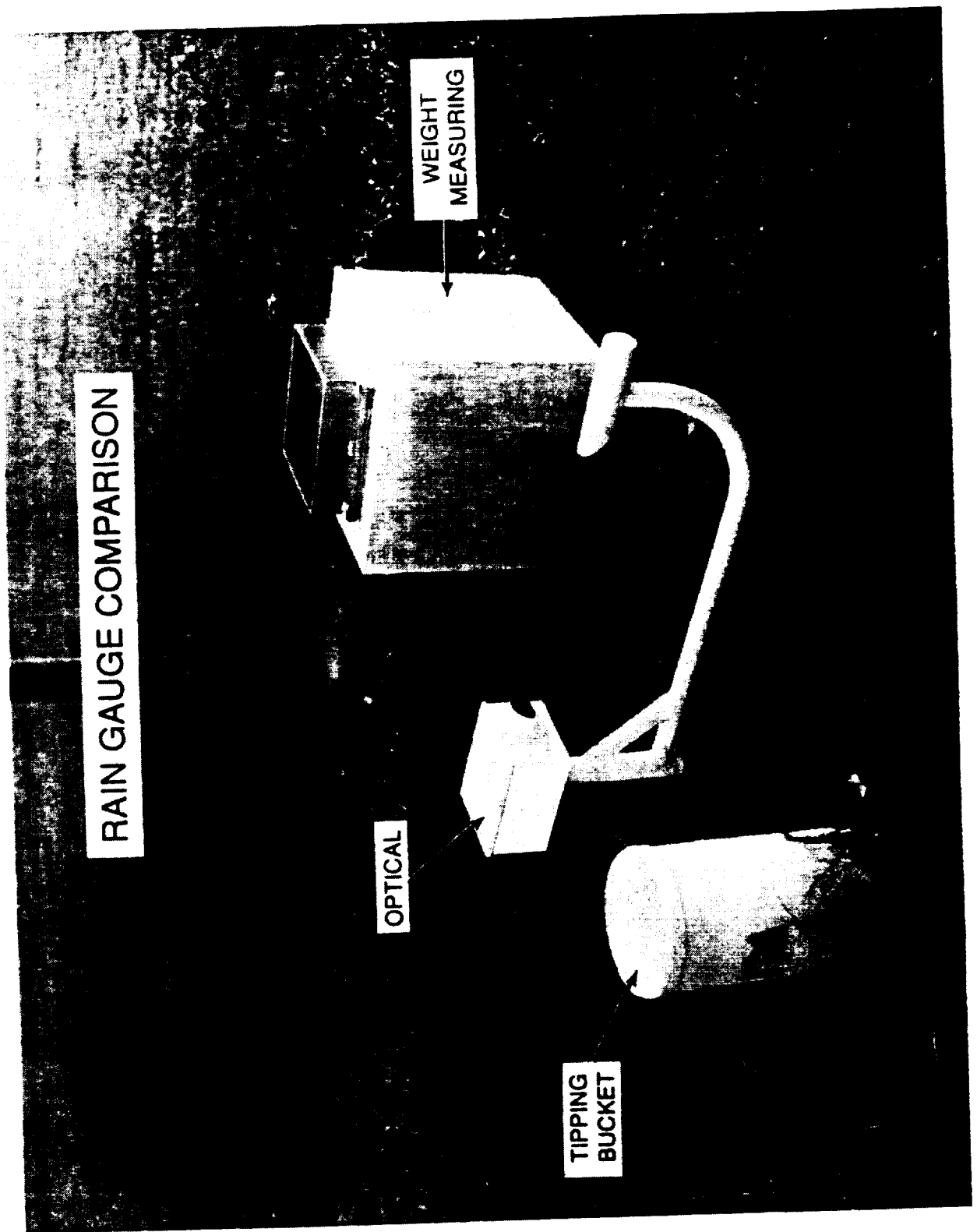


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(Bezoz, Dunham, Campbell, Melson: 1990)



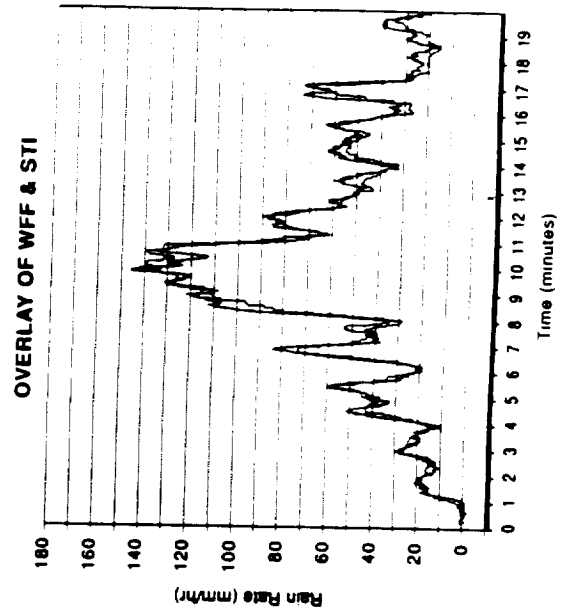
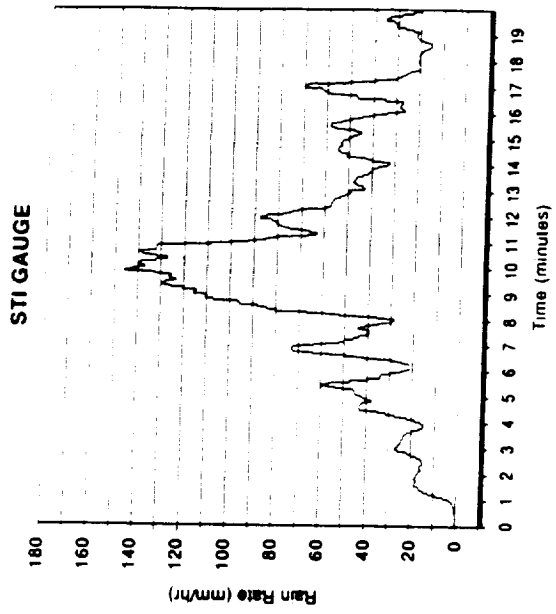
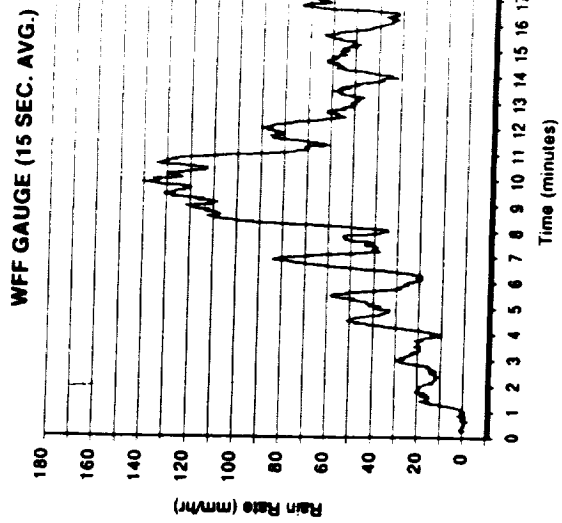


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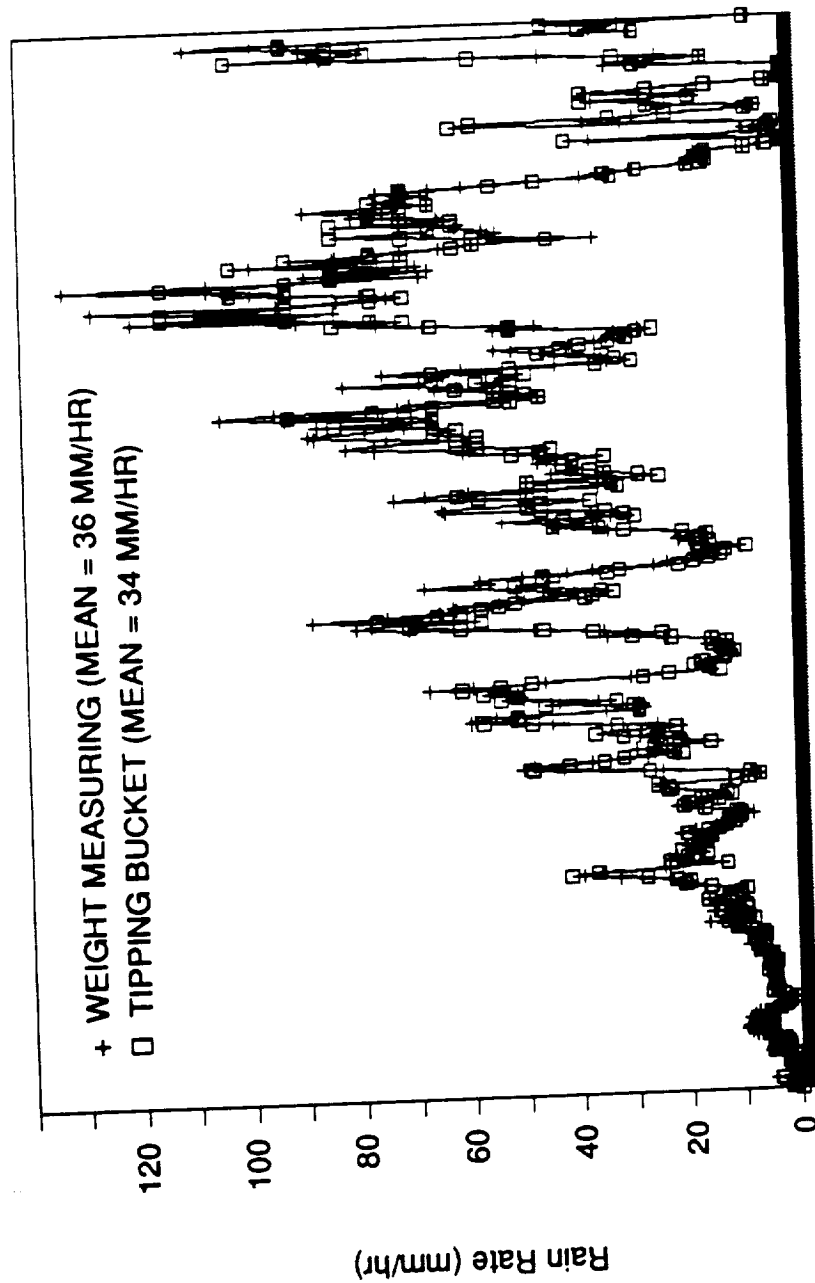
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RAINFALL EVENT

12/21/89 (Start 21:38:37)
 Darwin, Australia File # E6.7



COMPARISON OF THE WEIGHT MEASURING RAIN GAUGE TO A CONVENTIONAL TIPPING BUCKET RAIN GAUGE



LOCATIONS

- GSFC/WFF, WALLOPS ISLAND, VA (FEBRUARY 1989)
- LaRC, HAMPTON, VA (JUNE 1989)
- KSC, KENNEDY SPACE CENTER, FL (JUNE 1989)
- NASA/BMRC, DARWIN, AUSTRALIA (NOVEMBER 1989)
- BOEING AIRCRAFT CO., SEATTLE, WA (JANUARY 1990)
- NCAR/NWS, DENVER, CO (FEBRUARY 1990)

REDUCTION OF THE WEIGHT-MEASURING RAIN GAUGE RAINFALL DATA

○ **ACCUMULATOR**

○ **RESOLUTION**

○ **DIFFERENTIATION**

○ **TIME**

SYSTEM CALIBRATION

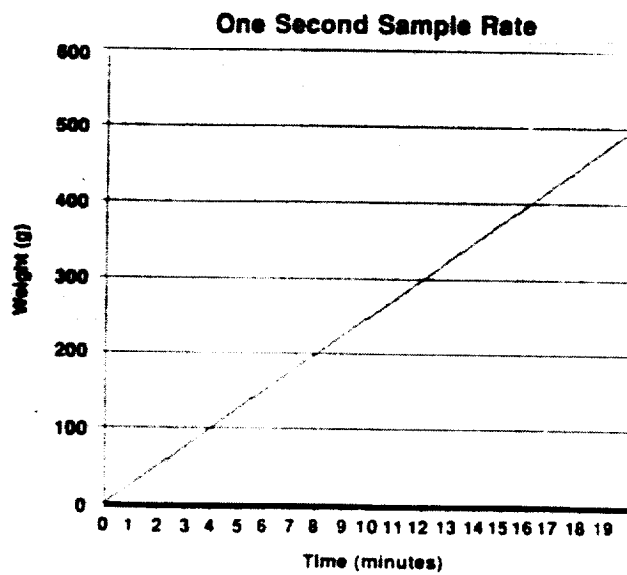
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Calibration
Bottle

VWR

Weight
Measuring
Rain Gauge

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EXAMINE THE HEAVY RAINFALL CHARACTERISTICS

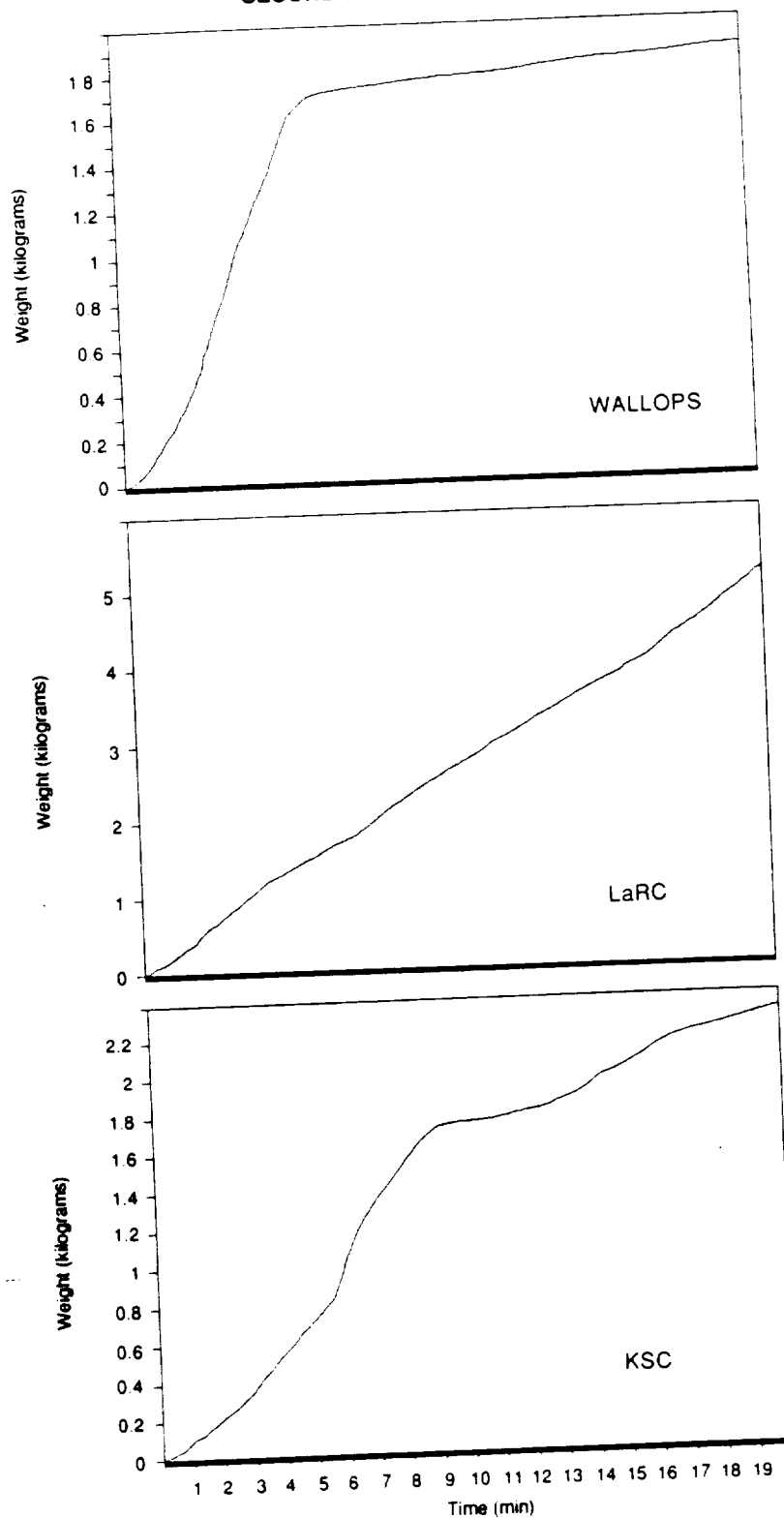
- **HEAVY RAIN RATE LEVELS**
- **DURATION OF DOWNPOURS**
- **FREQUENCY OF HEAVY RAINFALL**

SUMMARY

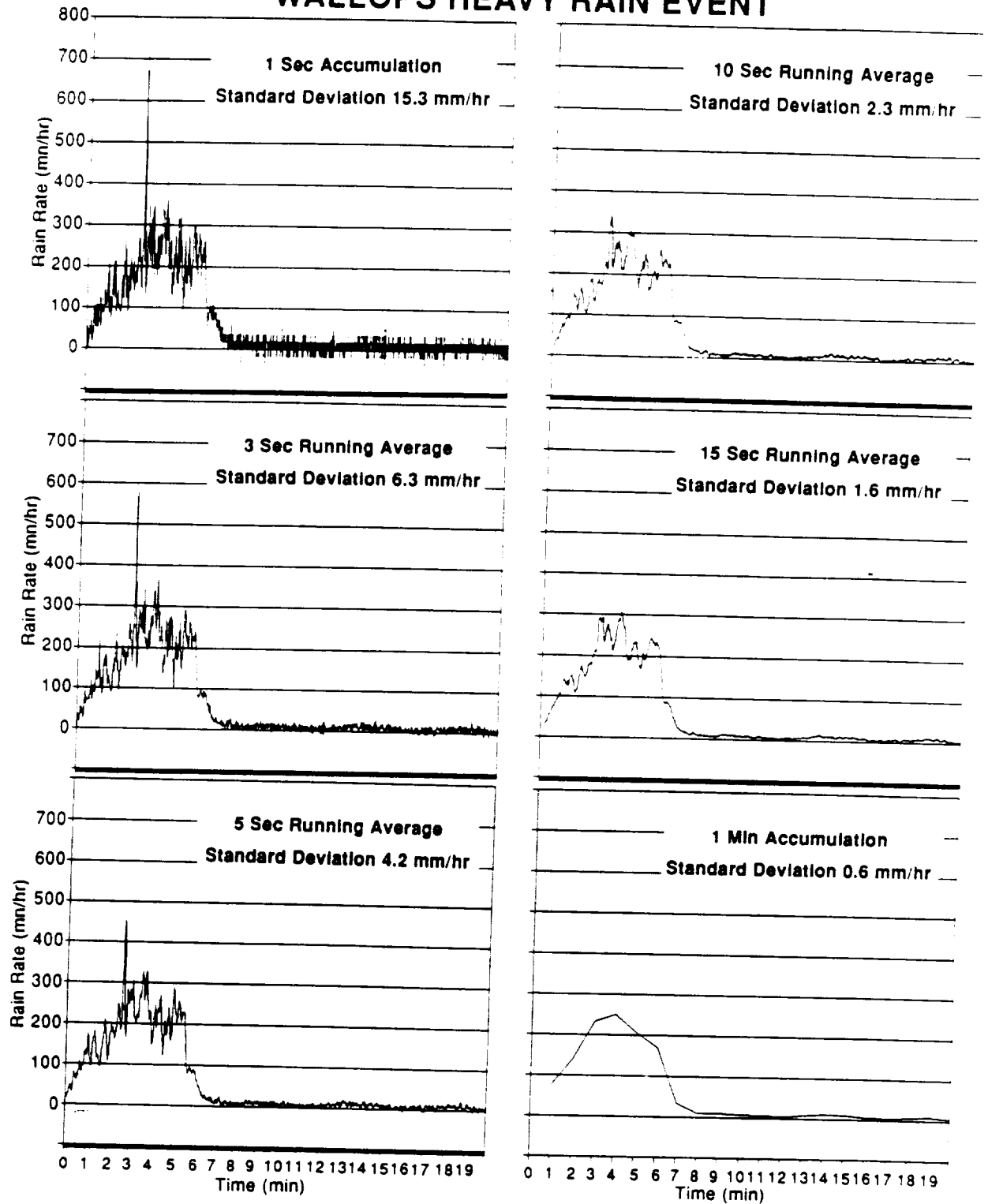
<u>LOCATION</u>	<u>MONTHS</u>	<u>GAUGE* OPERATIONAL TIME (SEC)</u>	<u>DATA POINTS</u>	<u>DATA POINTS GREATER THAN 100 MM/HR</u>	<u>MEAN RAIN RATE (MM/HR)</u>	<u>MAXIMUM RAIN RATE (MM/HR)</u>
DARWIN	5	11,741,760	285,600	3,361	10	299
KSC	9	21,072,960	255,600	4,123	10	492
LaRC	4	9,564,480	122,400	1,158	4	633
WALLOPS	15	35,303,040	910,800	4,142	5	722
DENVER	5	11,664,000	262,800	30	1	123
SEATTLE	6	14,074,560	366,000	10	1	105
TOTALS	-----	103,420,800	2,203,200	13,094	-----	-----

*ASSUME GAGE IS 90% OPERATIONAL DURING MONTHS IN SERVICE

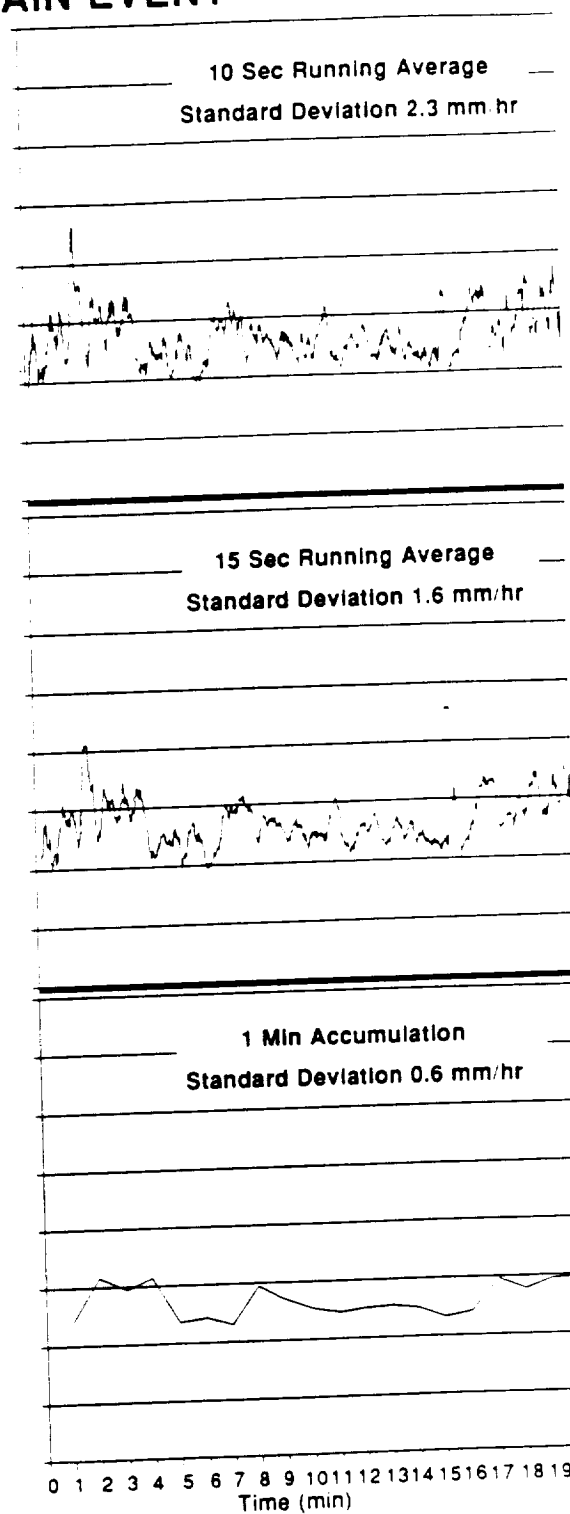
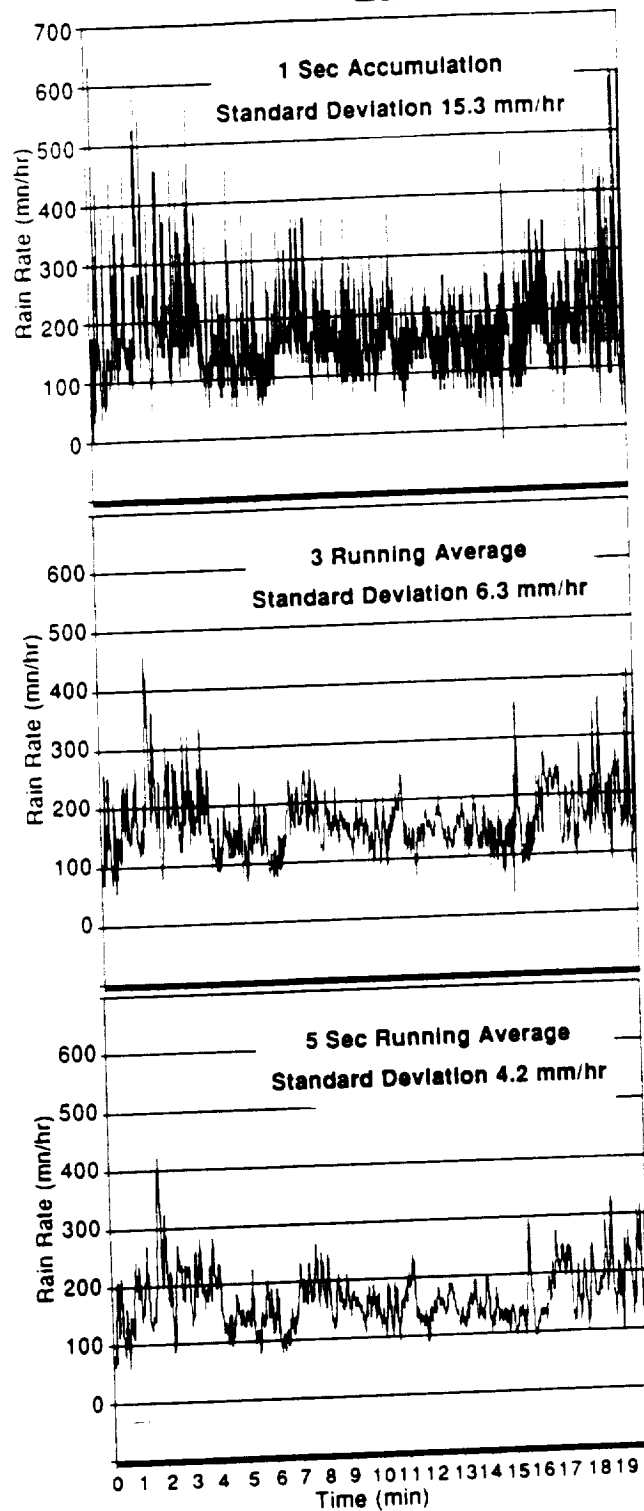
COLLECTED RAIN WATER WEIGHT FOR 20 MINUTES AT A ONE
SECOND SAMPLE RATE



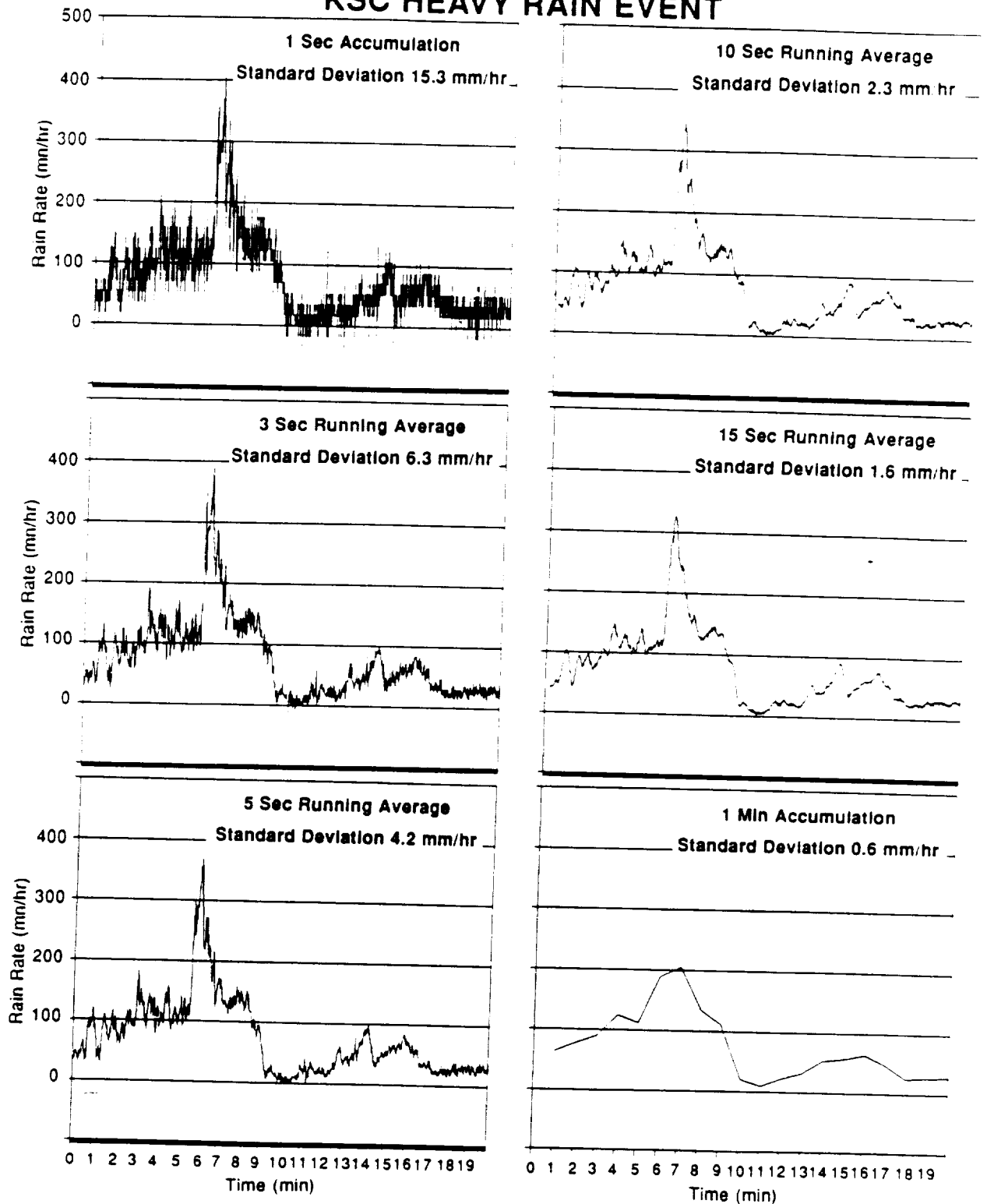
WALLOPS HEAVY RAIN EVENT



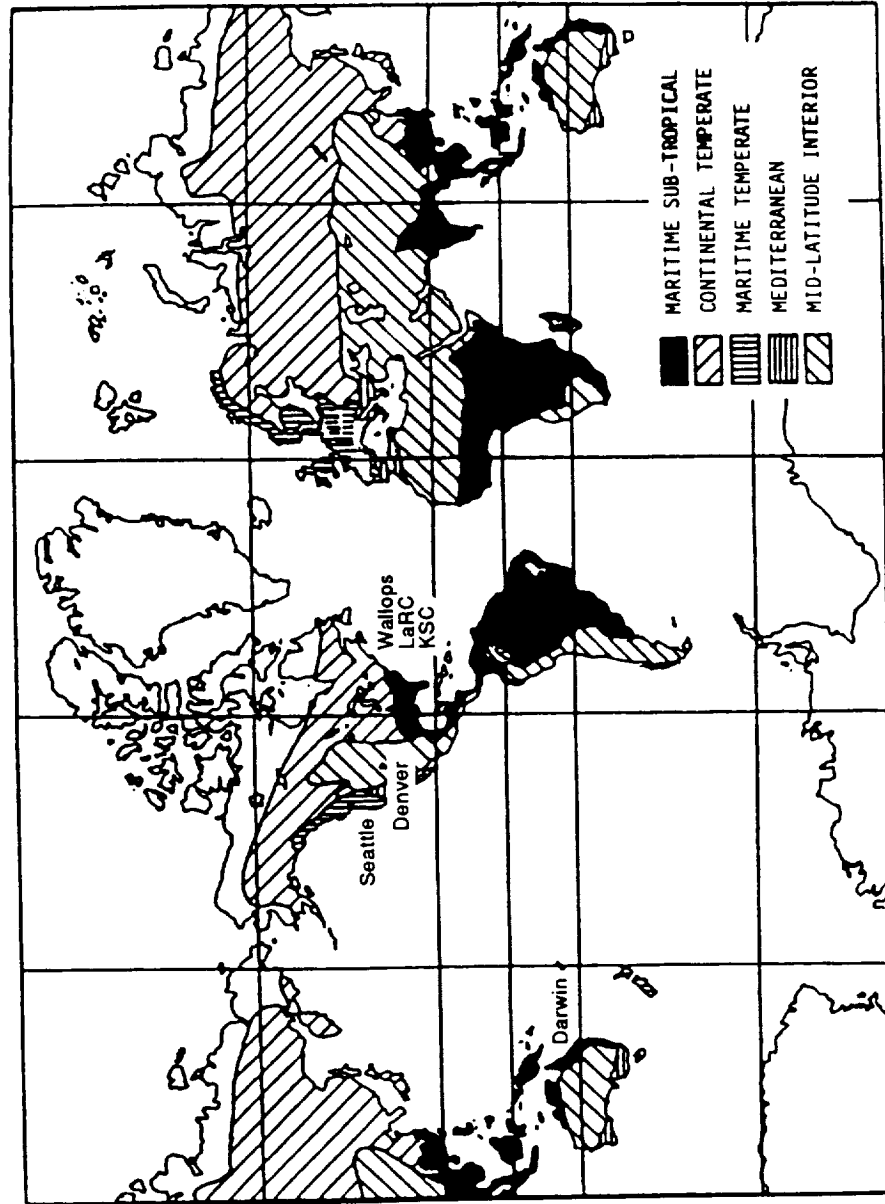
LaRC HEAVY RAIN EVENT



KSC HEAVY RAIN EVENT

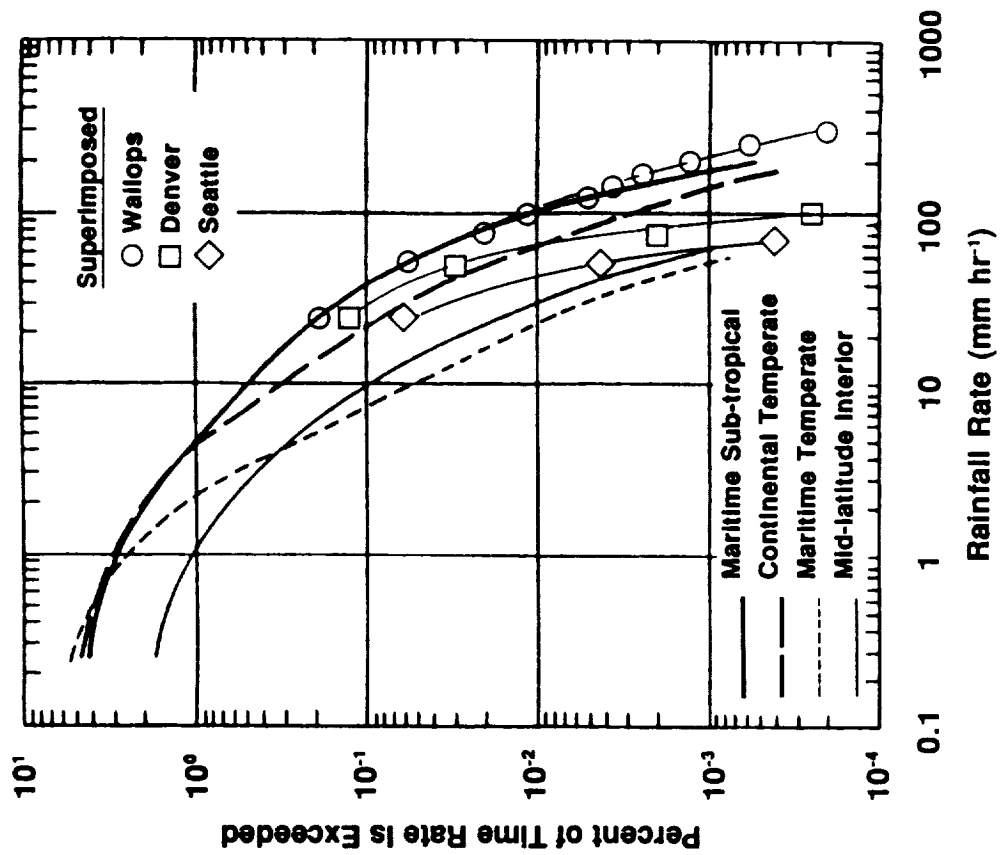


RAIN CLIMATES OF THE WORLD



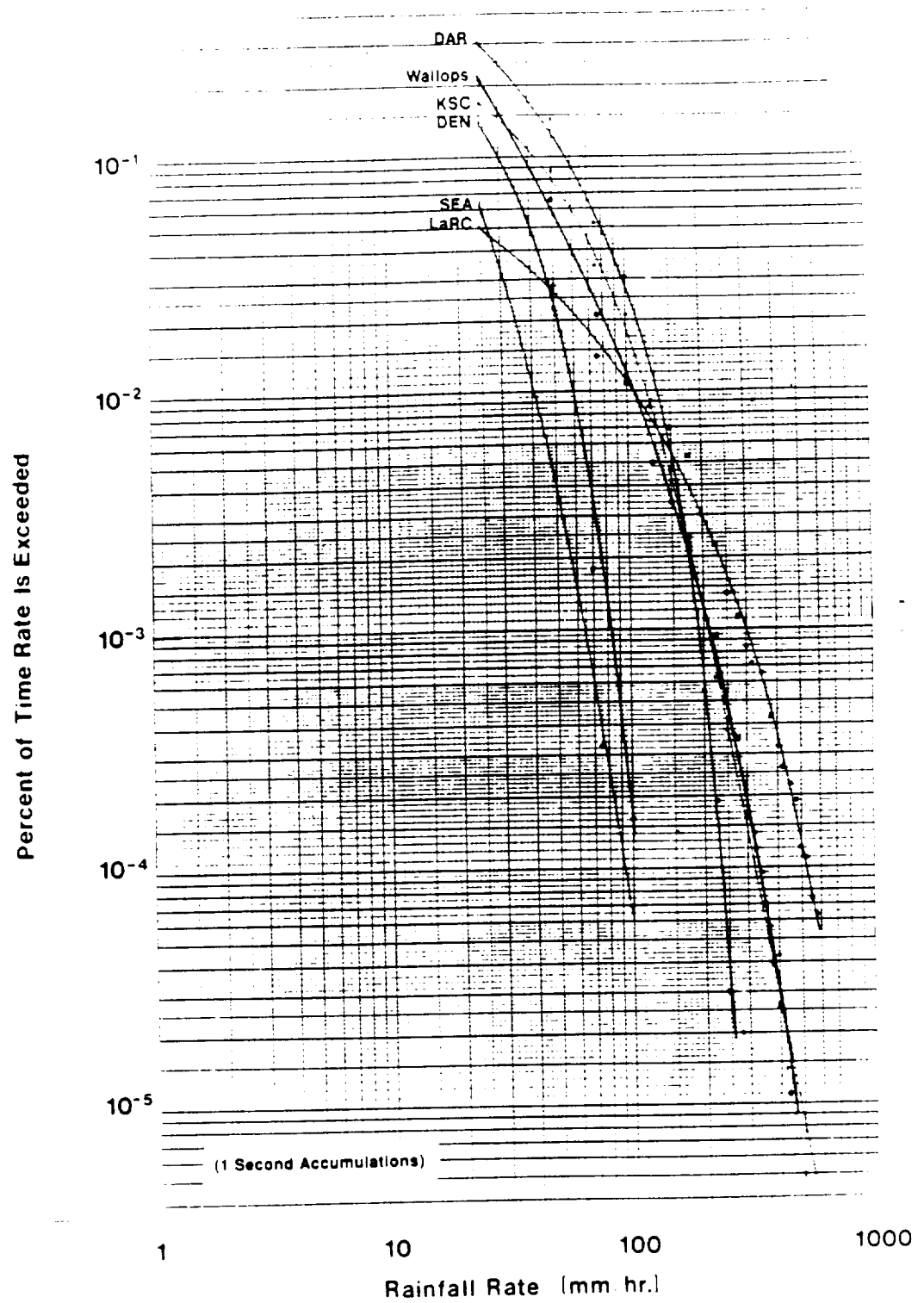
(Herbstritt, 1973)

RAINFALL RATE – FREQUENCY RELATIONSHIPS

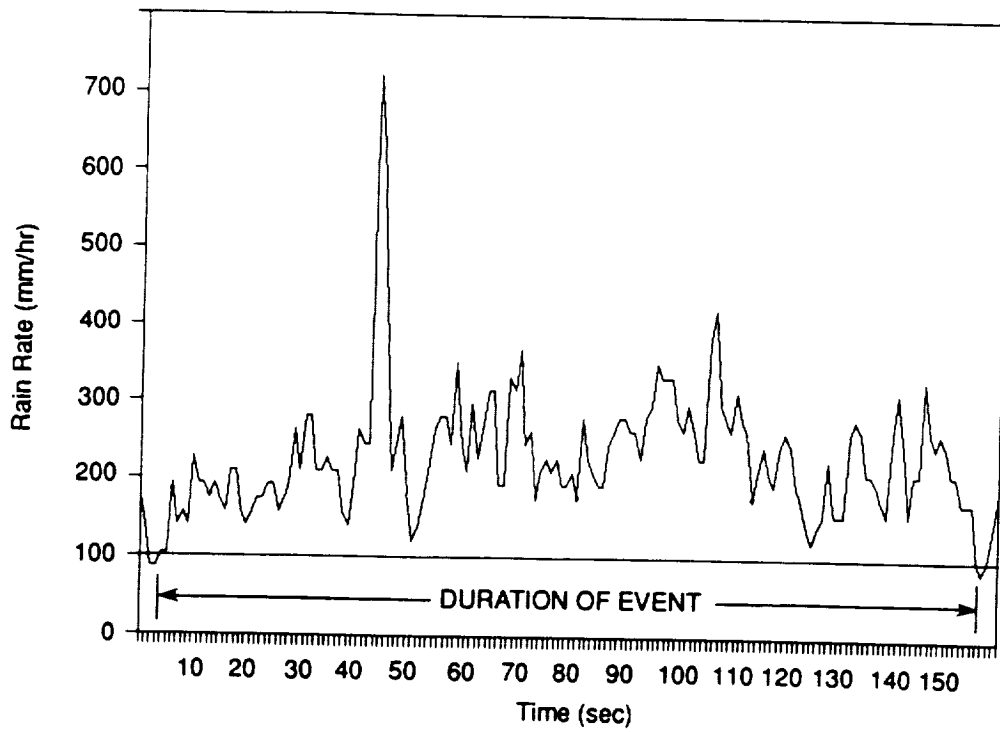


Jones & Sims, 1978: Climatology of Instantaneous Rainfall Rates (as defined by 1 and 4 minute accumulations)

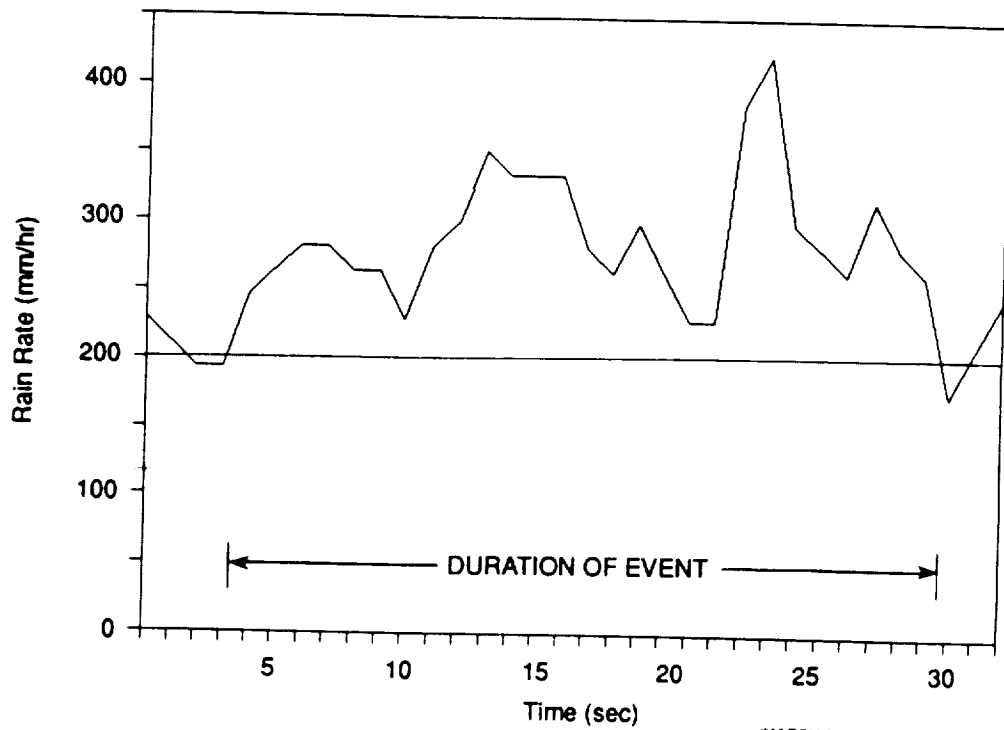
Rainfall Rate - Frequency Relationships



RAINFALL EVENT EXCEEDING 100 MM/HR



RAINFALL EVENT EXCEEDING 200 MM/HR



(MARCH 31, 1988 AT GSFC/WFF)

NUMBER AND DURATION OF HEAVY RAINFALL EVENTS

in/hr mm/hr	NUMBER OF EVENTS EXCEEDING					
	3.9 100	7.9 200	11.8 300	15.7 400	19.7 500	23.6 600

DURATION (SEC)	4705	630	129	48	18	4	1
01-10							
11-20	131	8					
21-30	41	5					
31-40	22						
41-50	16						
51-60	8						
>61	14						

SUMMARY

500 MM/HR (19.7 IN/HR) RAIN RATE EVENTS OCCUR IN NATURE AT A FREQUENCY THAT SUPPORTS THE NEED TO CONDUCT ALDF TESTS AT 500 MM/HR SIMULATED RAIN RATES

Heavy Rain Field Measurements - Questions and Answers

Q: ANDY PECZALSKI (Honeywell) - What are typical velocity values of rain droplets? Is there any correlation between droplet velocity and rain rate? Where can I find this information?

A: ED MELSON (NASA Wallops) - I'm going to have to quote that from memory, so it will be an order of magnitude. A small droplet, say in the order of 1/2 millimeter, would fall around 2 millimeters per second and a large droplet, in the order of 4 millimeters diameter, would fall somewhere in the order of 8 millimeters per second. This data was from Gunn and he related the fall velocity of droplets. The larger droplets he said follow Newtonian physics, whereas the small droplets with Stokes. The relationship is indirect in that we are looking at the velocity of droplets. If you want to relate that to rainfall rate, the Marshall-Palmer Report, relates drop size to rain fall rate, so indirectly you could relate fall velocity to rain rate. But from the reports I've seen it's mostly drop size distribution related to rain fall rate.

Q: NORMAN CRABILL (Aero Space Consultants) - Have you correlated any of the rain rate measurements with radar measurements?

A: ED MELSON (NASA Wallops) - No, I haven't at this time. We do have three of our gauges in locations within the range of radars. The one at Denver is under radar coverage, and the one in Florida is also under radar coverage. The one in Darwin is being moved so it will be in a better position to be under radar coverage. I know that the data at Kennedy is being evaluated. The data at Darwin is going to be evaluated by the Tropical Rain Measurement Mission people. They are using a satellite based radar and they are concerned about the Z versus R curve, so they are using ground point measurement devices to validate these radars.

Q: CHET EKSTRAND (Boeing) - Field measurements apparently only involve sampling at a single geographical position at each site. What do we know about the distribution of rain rates over a large geographical area at a single site? In other words, in an environment where significant wind shear might occur, how long might an airplane moving at typical approach speeds be continuously exposed to rain rates which have significant effects on aircraft climb performance or stall margin? Do you have any plans to do simultaneous sampling at several geographic positions at a single site?

A: ED MELSON (NASA Wallops) - We're right now purchasing 3 gauges to put in one single site so we can get an idea of what is the graphical positioning area of some of these storms. I think some of this work has been done. I know the WMO, which is the World Meteorological Organization, in their report on the probability of maximum participation have looked at how large some of these cells are, and I'm sure this group has looked at how large some of the microburst cells are also. I don't particularly know how large some of them are, nor do I know exactly how long it would take an aircraft to fly through these cells. But I think that's something that we are going to have to address as soon as we get most of our information together from some of the tests that we are doing at these sites and also in the wind tunnel. The question on are we looking at rain data in a microburst, the site at Darwin, Australia, is particularly being set up to look for some of that type of data right now. We had a report from Tom Keenan of Australia who indicated that they were seeing from the Toga radar on the average of five microbursts a week during the transition from the monsoon season to the convective storm. At this time there is going to be a weight measure rain gauge, a tipping bucket, and optical gauge and a distrometer to

measure drop size, located at a site in which the Toga radar will be able to overlook it. This is planned to be conducted this winter here, they're summer there.

Session VI. Heavy Rain Aerodynamics

N 9 1 - 2 4 1 8 2

Estimate of Heavy Rain Performance Effect
Dan Vicroy, NASA Langley

The Aerodynamic Effect of Heavy Rain on Airplane Performance

Dan D. Vicroy
NASA Langley Research Center
Hampton, Virginia

NASA / FAA Wind Shear Review Meeting
October 16-18, 1990
Hampton, Virginia

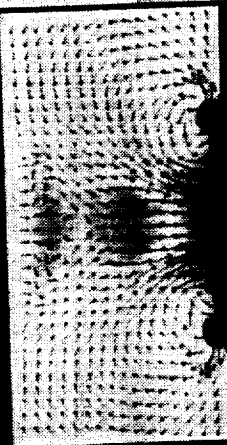
LaRC

The Aerodynamic Effect of Heavy Rain on Airplane Performance

NASA

NASA/FAA AIRBORNE WIND SHEAR PROGRAM ELEMENTS

Hazard Characterization



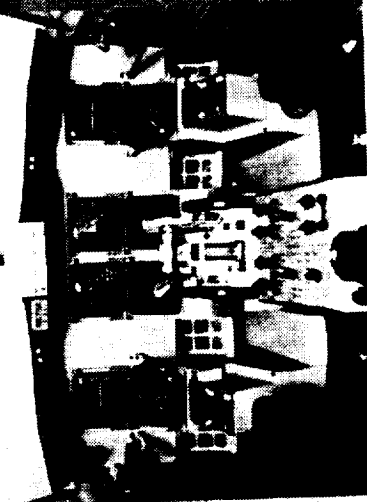
- Wind Shear Physics/Modeling
- Heavy Rain Aerodynamics
- Impact on Flight Characteristics

Sensor Technology



- 2nd Generation Reactive
- Airborne Doppler RADAR/LIDAR
- Airborne Passive INFRARED
- Sensor Information Fusion
- Flight Performance Evaluation

Flight Management Systems



- System Performance Requirements
- Guidance/Display Concepts
- TDWR Information Data Link/Display
- Pilot Factors/Procedures

AIAA HR bw 2

1/10/91

The Aerodynamic Effect of Heavy Rain on Airplane Performance

Objective:

Estimate and characterize the effect of heavy rain on the performance of a conventional twin-jet transport

Methodology:

- a) Develop a heavy rain aerodynamic model of the airplane based of 2D airfoil measurements
- b) Compute airplane performance with heavy rain model
- c) Numerically simulate a wet microburst encounter and exercise escape procedures

The Aerodynamic Effect of Heavy Rain on Airplane Performance

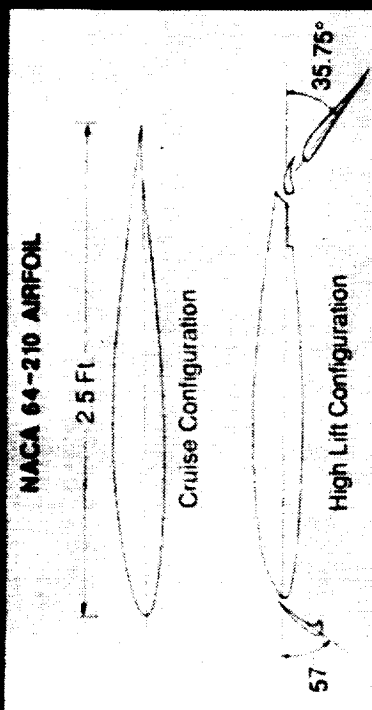
Outline

- Review of heavy rain airfoil tests
- Development of heavy rain aerodynamic model for a twin-jet transport
- Performance analysis with heavy rain effects
- Numerical simulation of wet microburst encounter
- Summary of Results & Future Needs

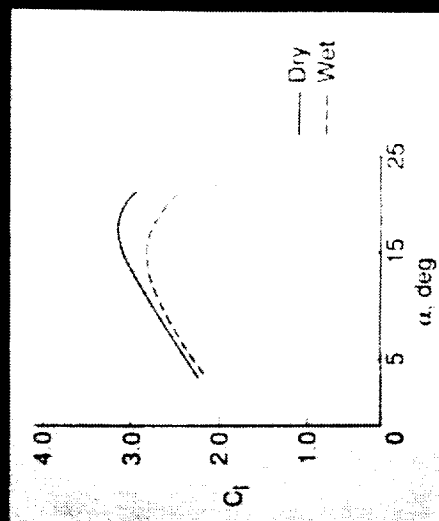
The Aerodynamic Effect of Heavy Rain on Airplane Performance

Rain Effects on Airfoil Performance

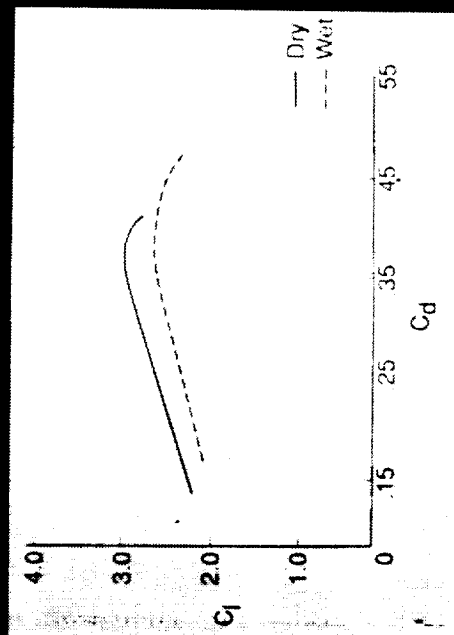
Cross Section of the Wing Model



High Lift Configuration



Test Set-up in 14 by 22 Foot Tunnel
with Simulated Rain

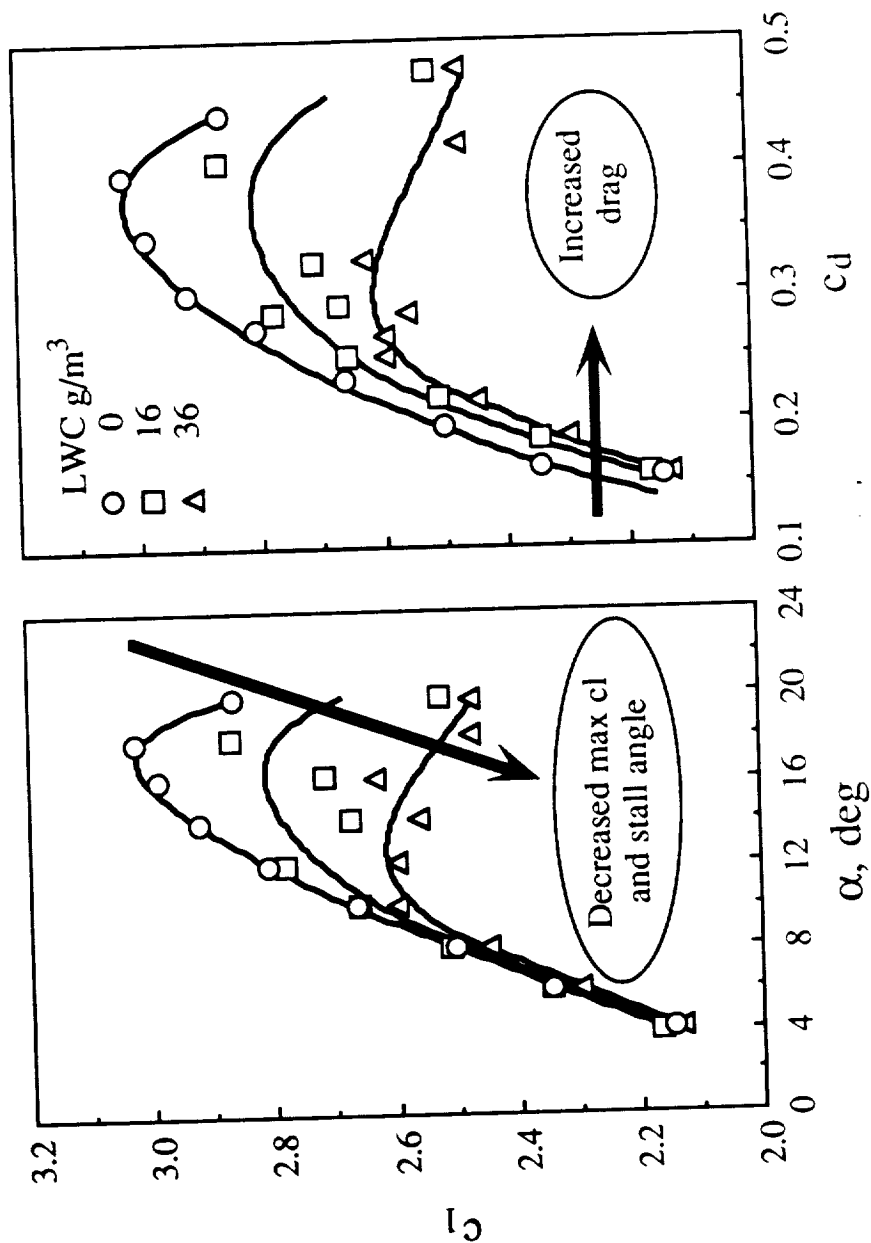


1/10/91

AIAA HR b/w 5

The Aerodynamic Effect of Heavy Rain on Airplane Performance

Heavy Rain Effect on NACA 64-210 in a High Lift Configuration



NASA

LaRC

The Aerodynamic Effect of Heavy Rain on Airplane Performance

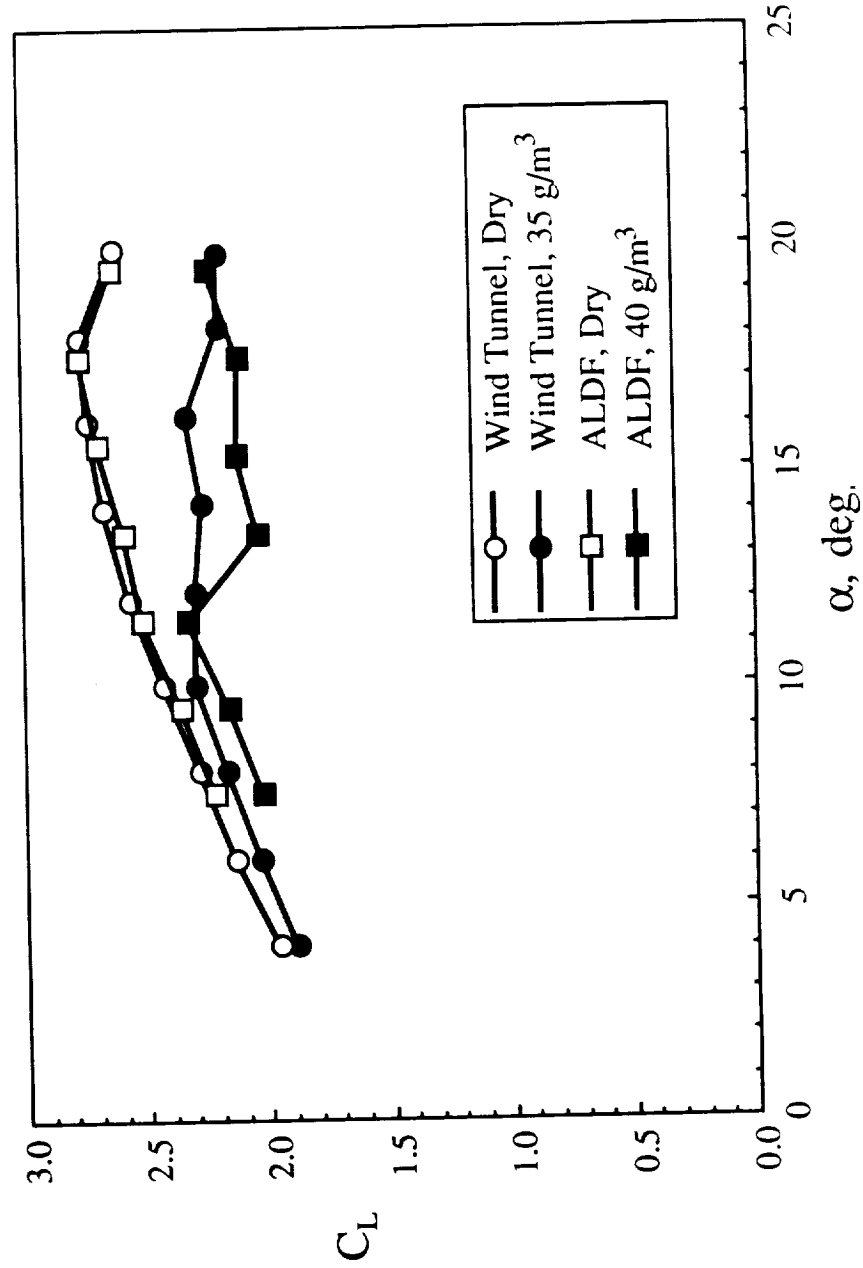


1/10/91

AIAA HR b/w 7

The Aerodynamic Effect of Heavy Rain on Airplane Performance

Heavy Rain Scale Effect



The Aerodynamic Effect of Heavy Rain on Airplane Performance

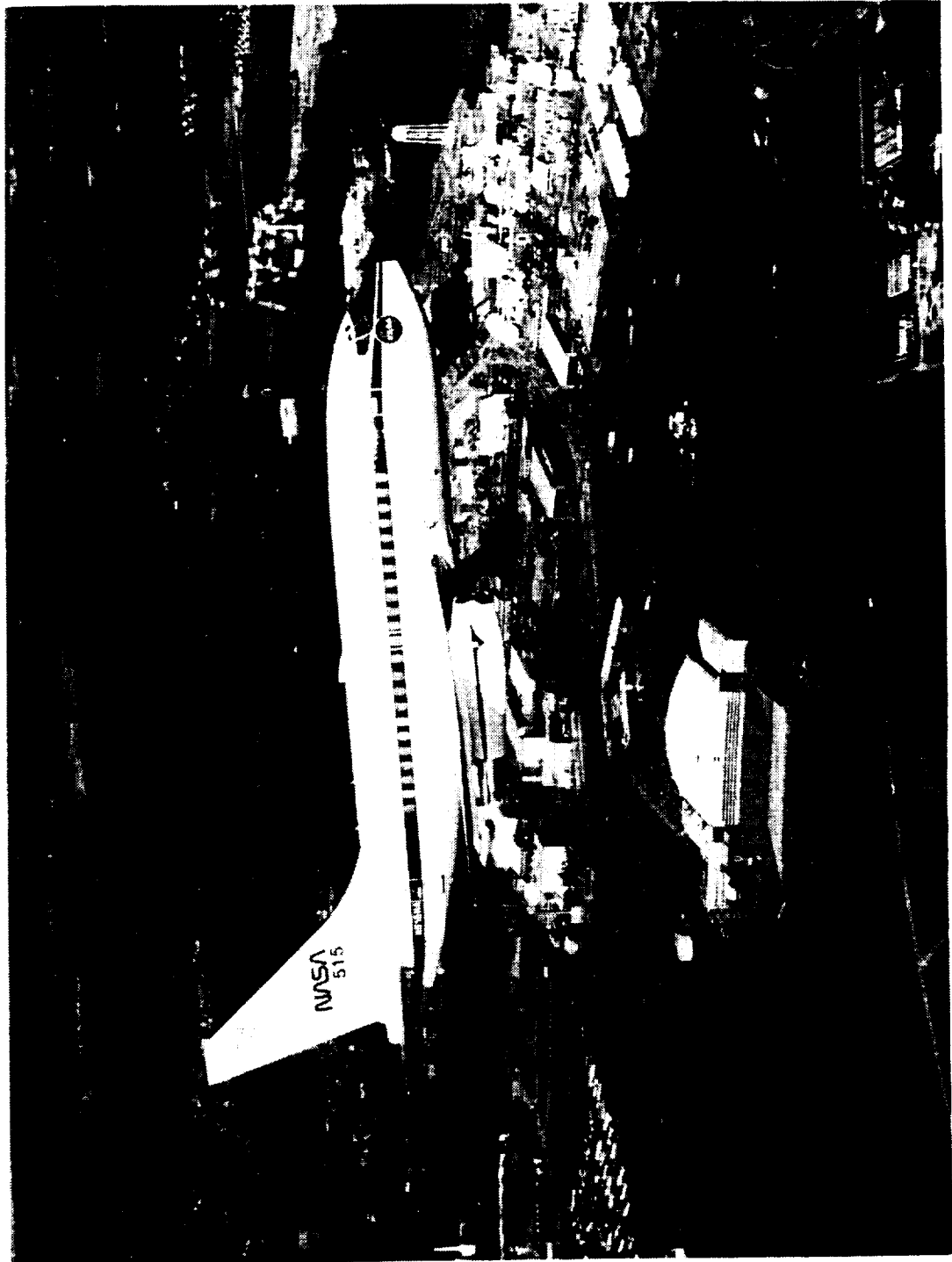
Outline

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NASA

LaRC

The Aerodynamic Effect of Heavy Rain on Airplane Performance

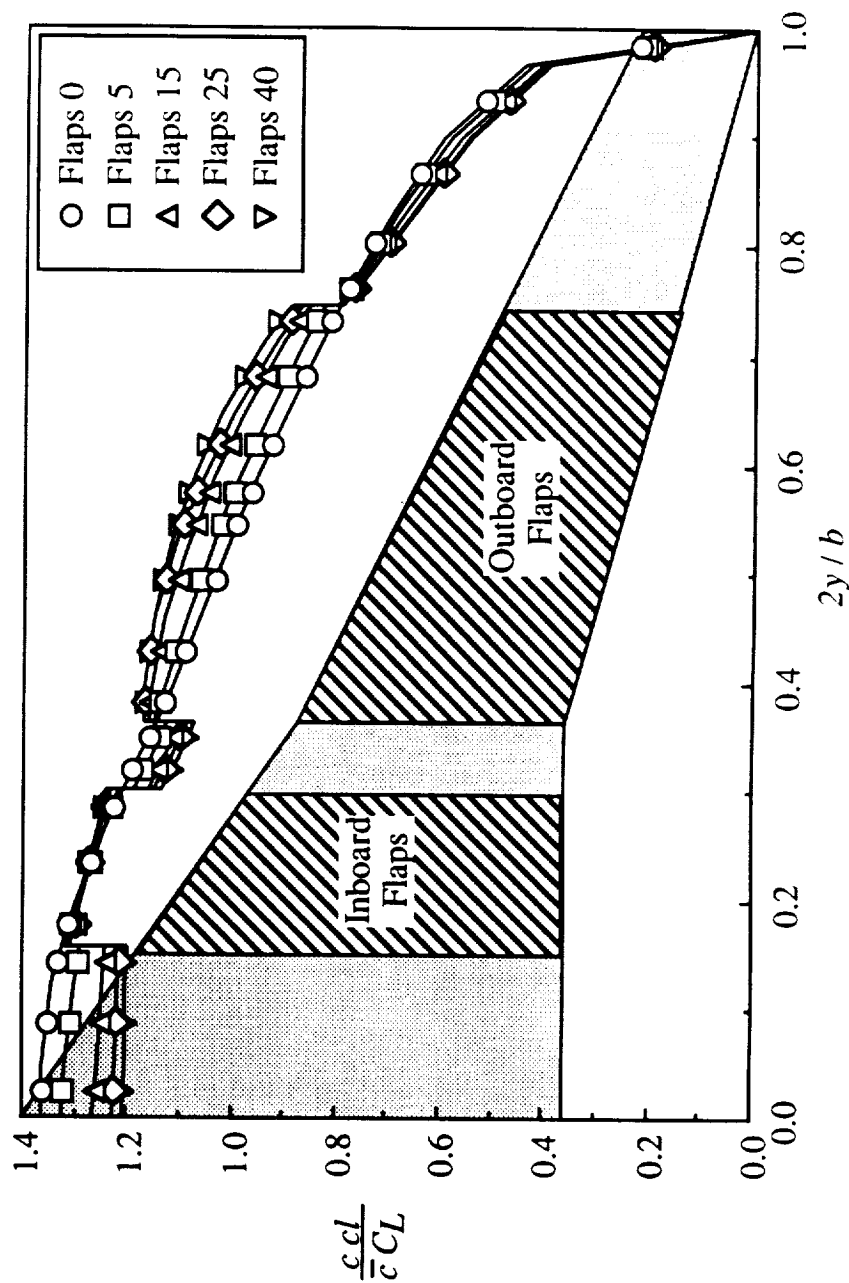


1/10/91

AIAA HR b/w 10

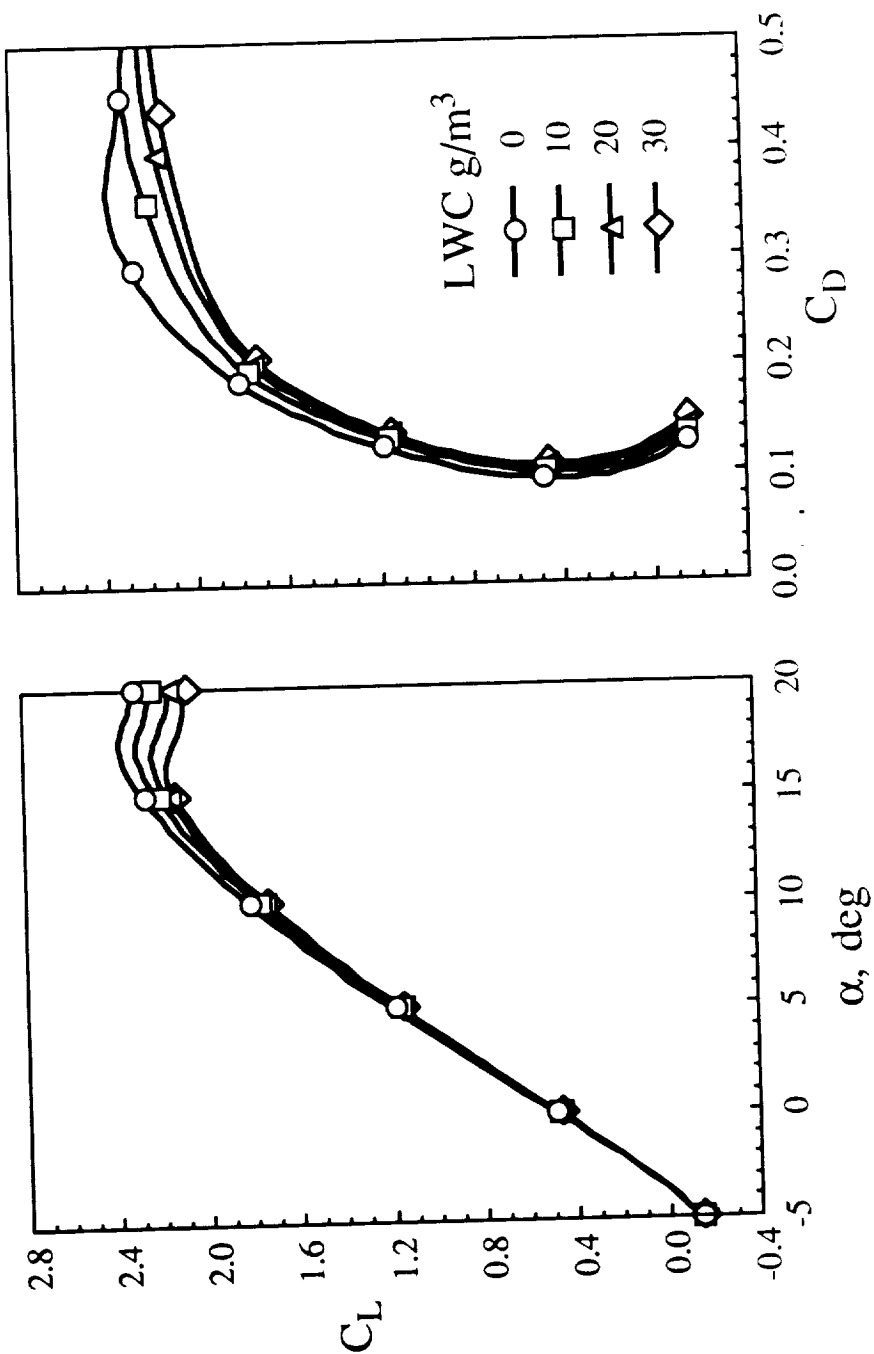
The Aerodynamic Effect of Heavy Rain on Airplane Performance

Planform Integration



The Aerodynamic Effect of Heavy Rain on Airplane Performance

Heavy Rain Aerodynamic Model (Flaps 25°, Gear Down)



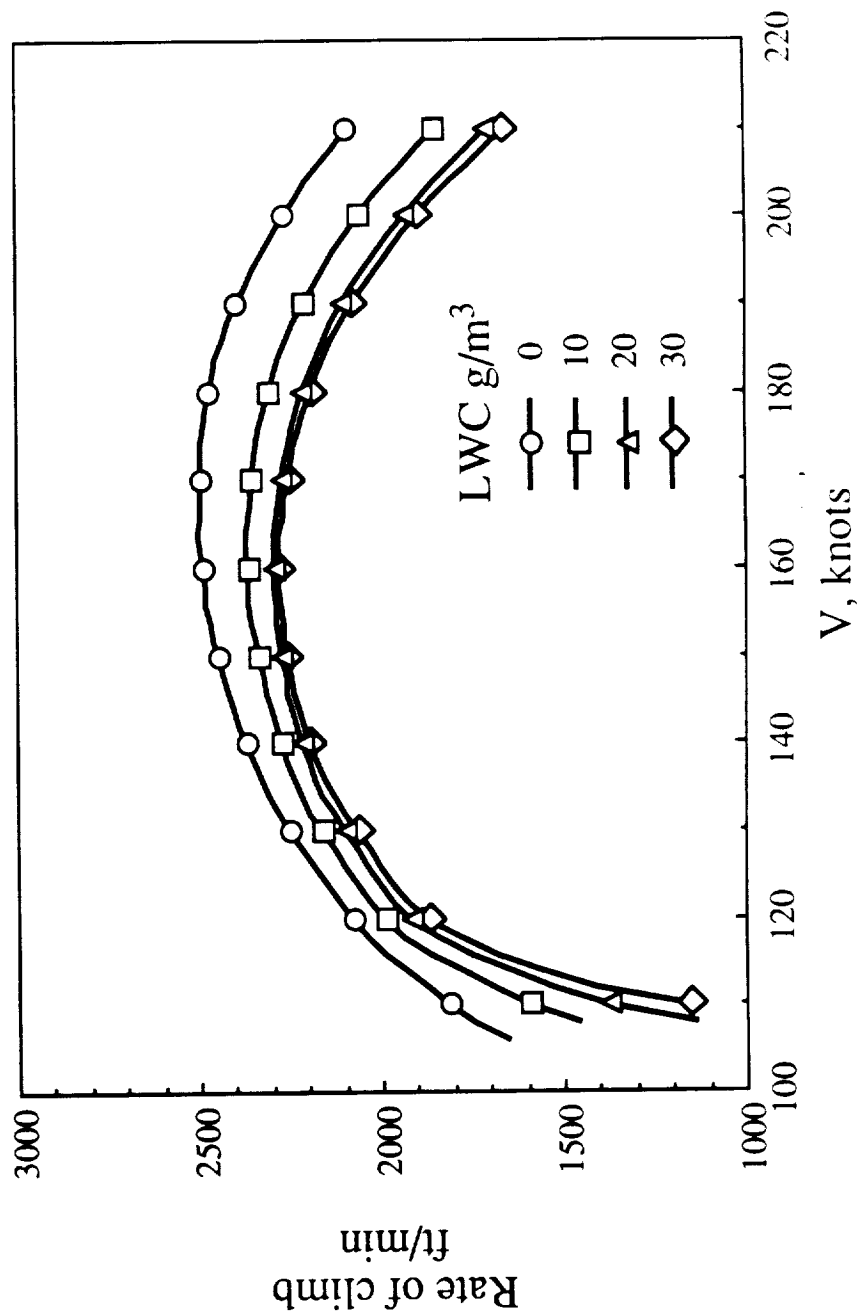
The Aerodynamic Effect of Heavy Rain on Airplane Performance

Outline

- Review of heavy rain airfoil tests
- Development of heavy rain aerodynamic model for a twin-jet transport
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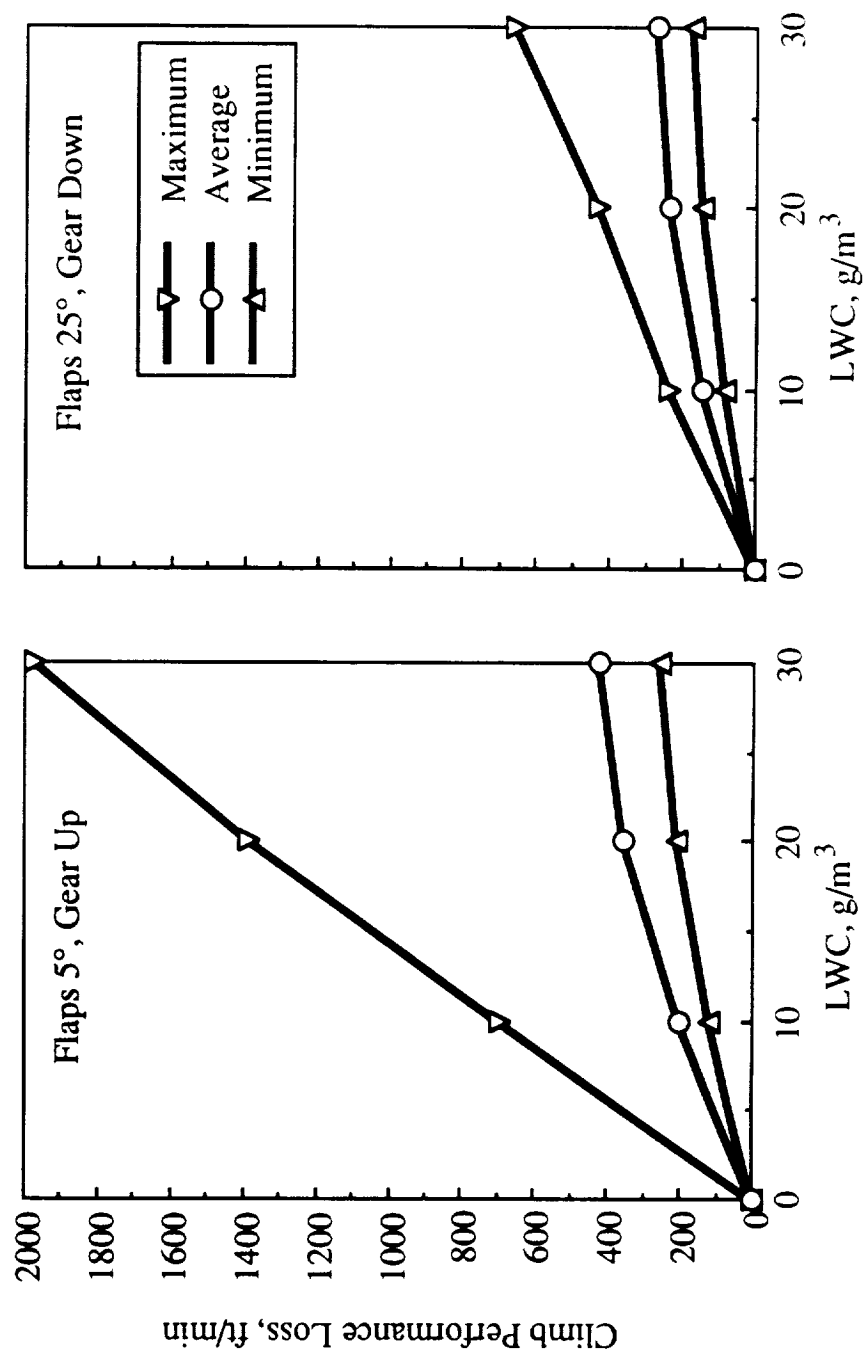
The Aerodynamic Effect of Heavy Rain on Airplane Performance

Climb Performance in Heavy Rain (Flaps 25°, Gear Down)



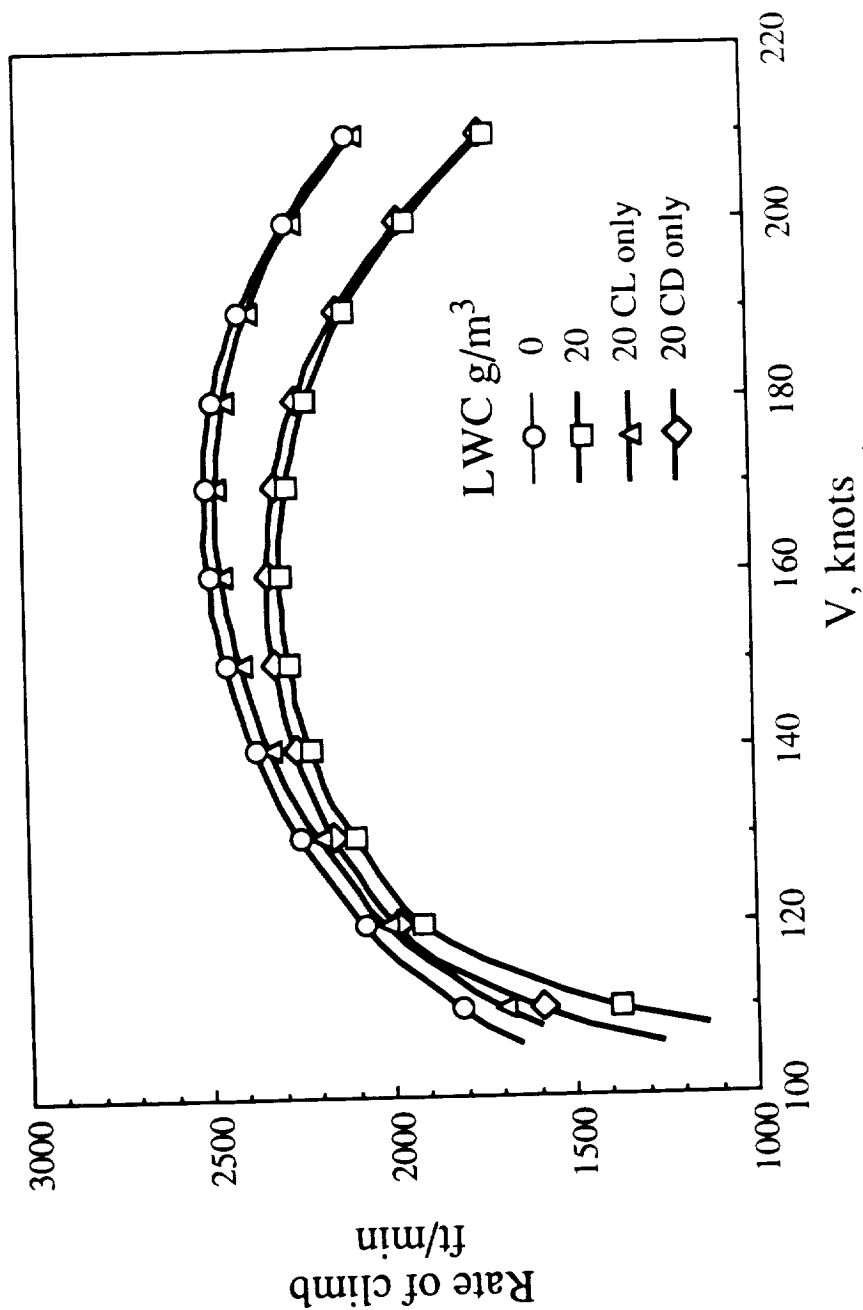
The Aerodynamic Effect of Heavy Rain on Airplane Performance

Climb Performance Loss



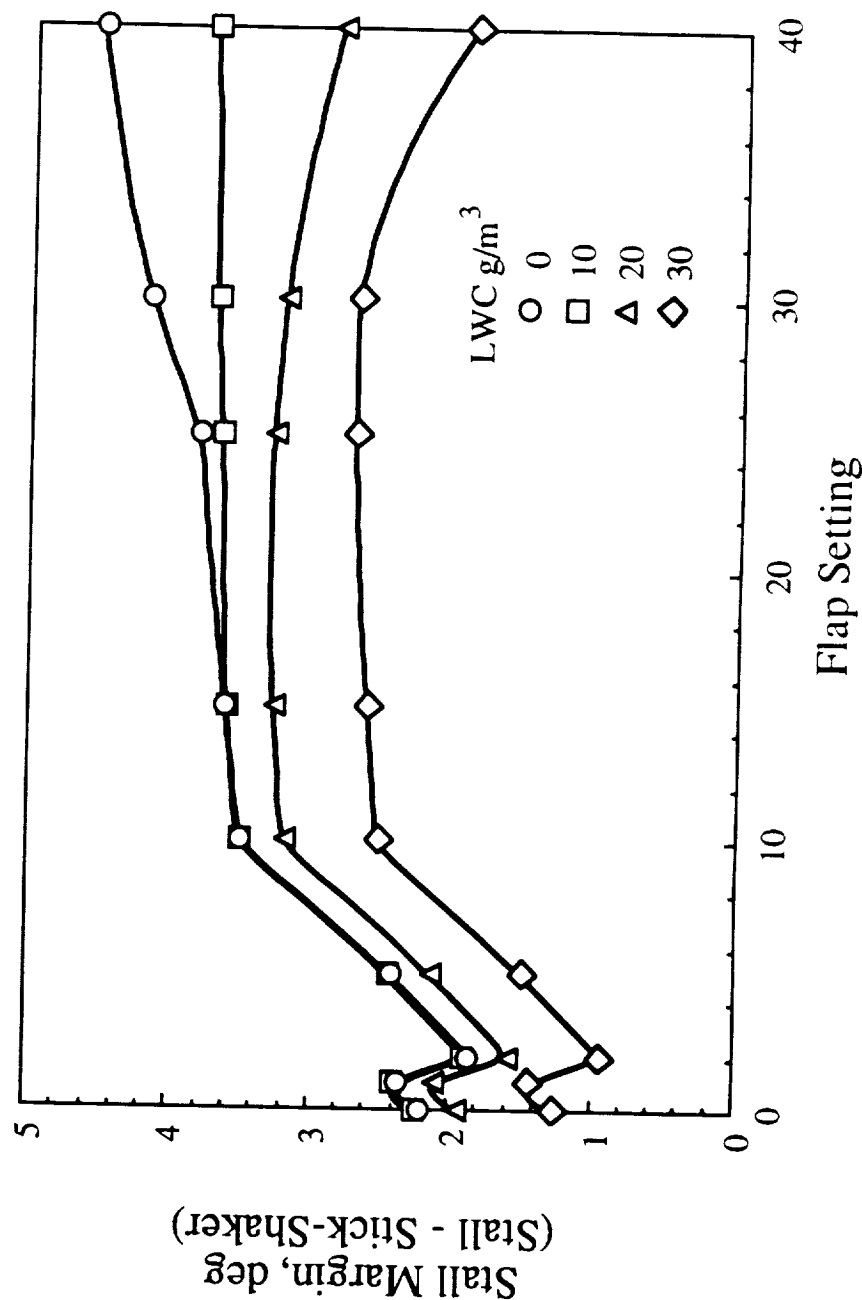
The Aerodynamic Effect of Heavy Rain on Airplane Performance

Climb Performance Sensitivity to Lift and Drag
(Flaps 25°, Gear Down)



The Aerodynamic Effect of Heavy Rain on Airplane Performance

Stall Margin



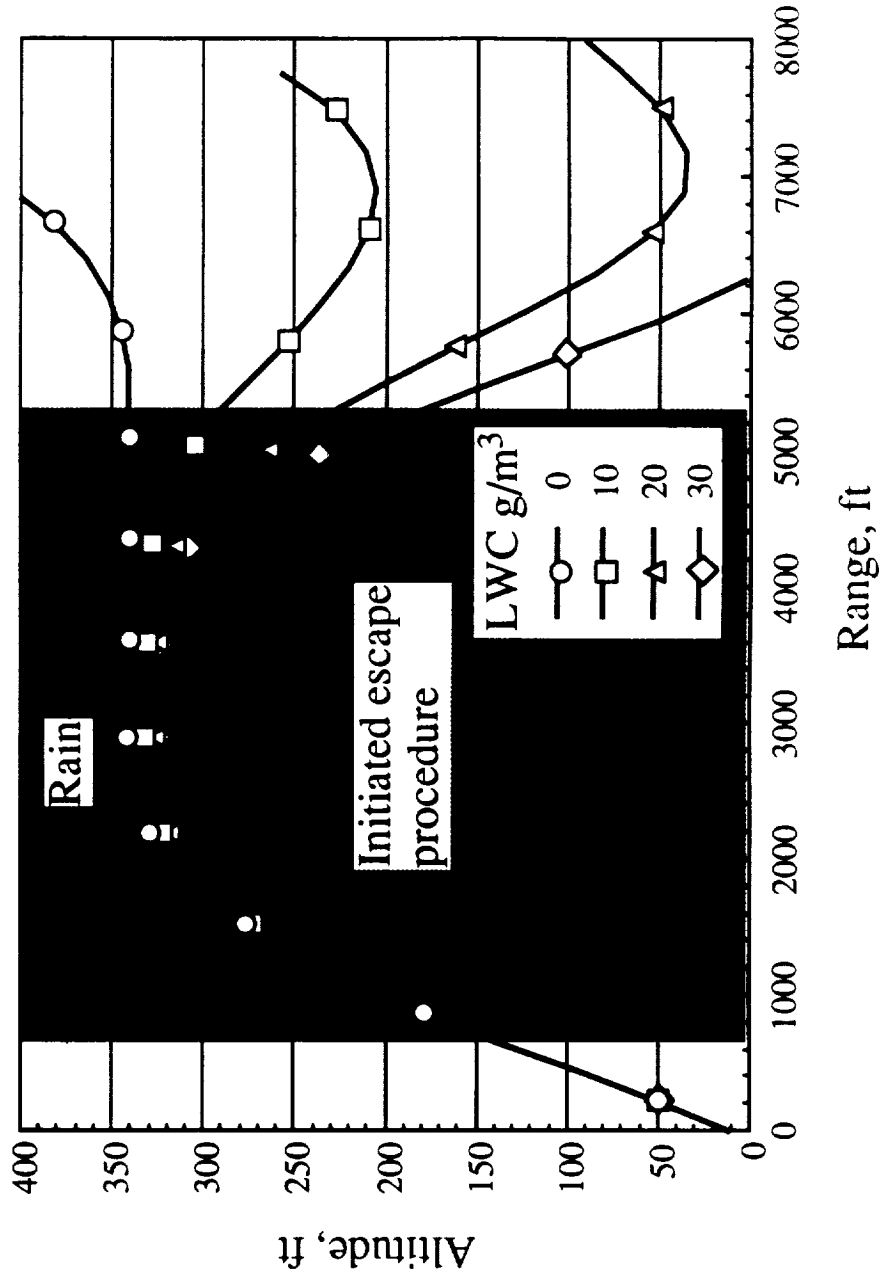
The Aerodynamic Effect of Heavy Rain on Airplane Performance

Outline

- Review of heavy rain airfoil tests
- Development of heavy rain aerodynamic model for a twin-jet transport
- Performance analysis with heavy rain effects
- Numerical simulation of wet microburst encounter
- Summary of Results & Future Needs

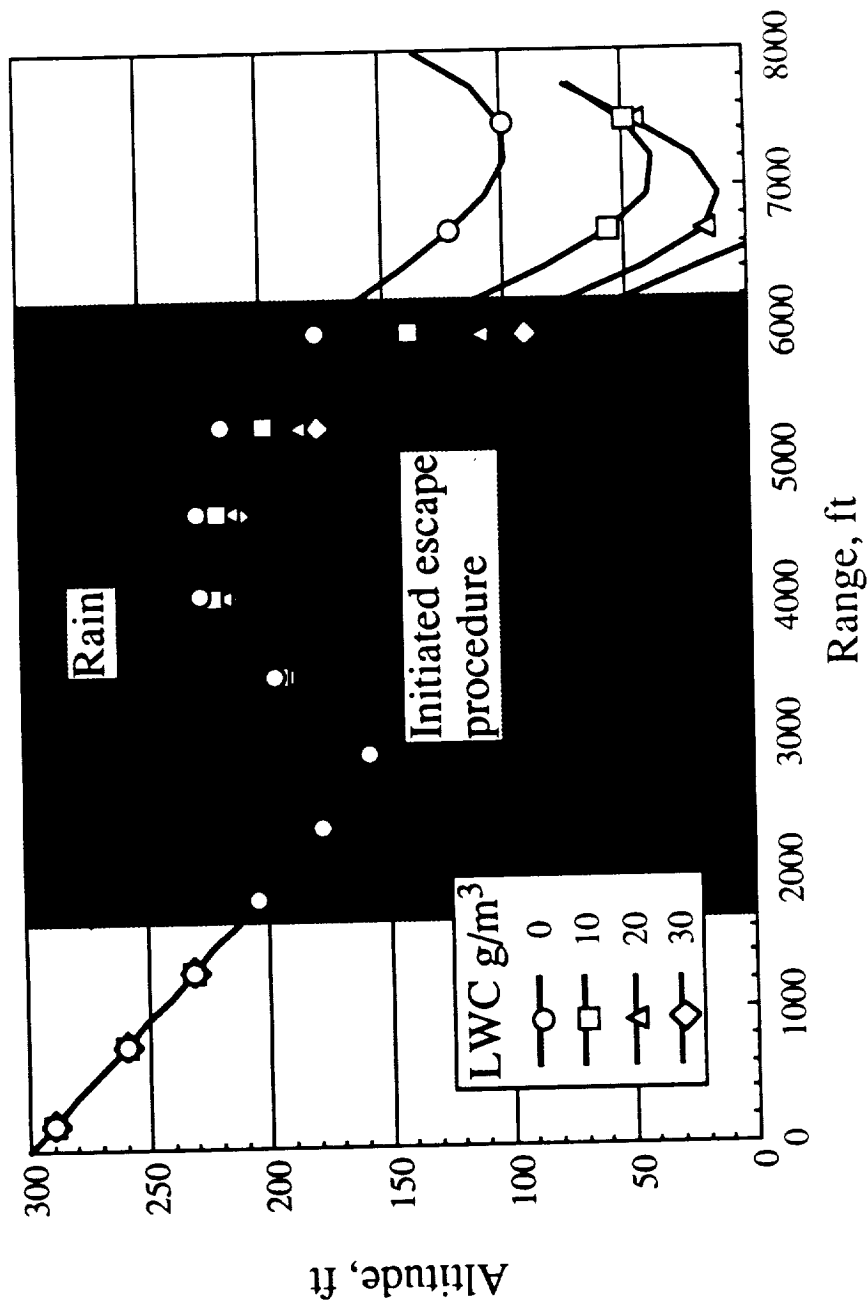
The Aerodynamic Effect of Heavy Rain on Airplane Performance

Wet Microburst Encounter on Take-off



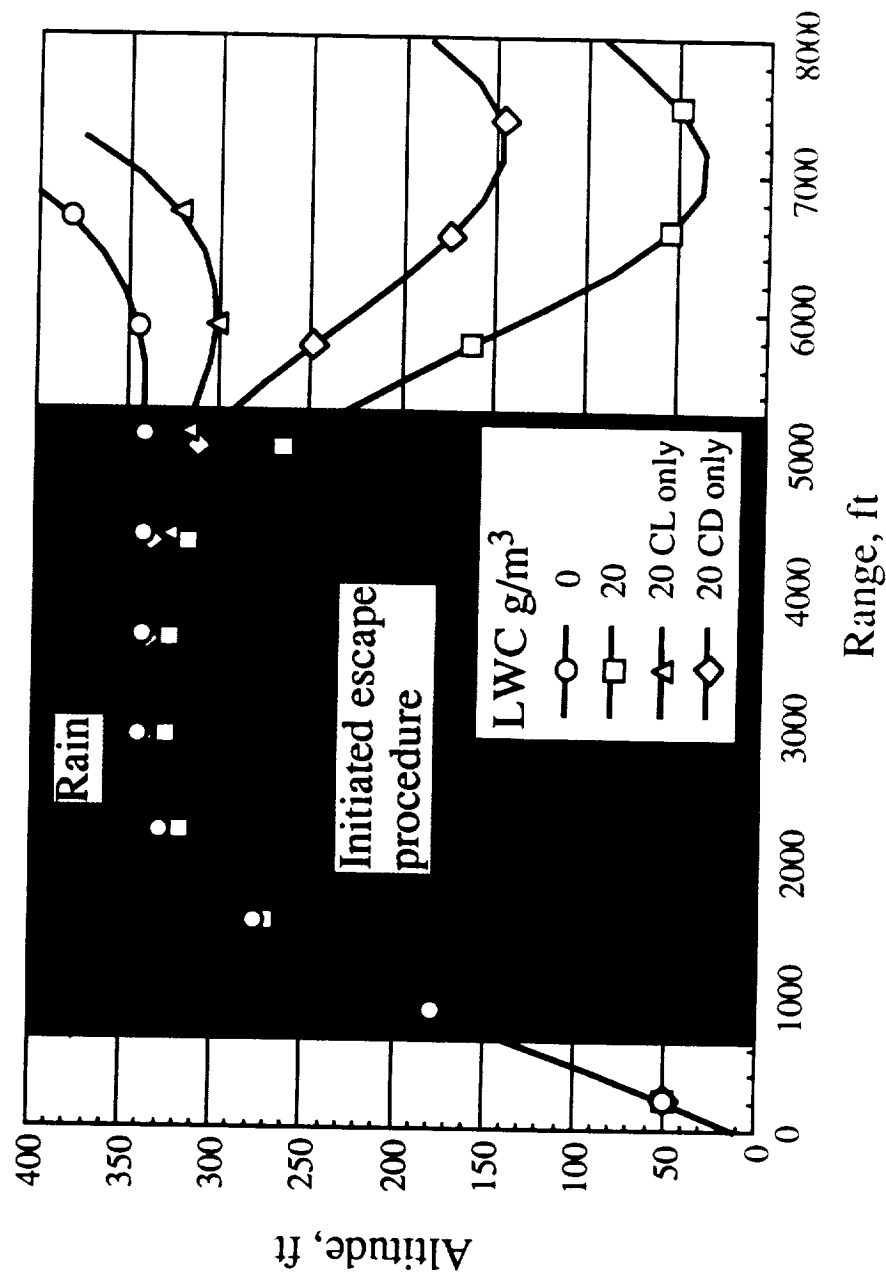
The Aerodynamic Effect of Heavy Rain on Airplane Performance

Wet Microburst Encounter on Approach



The Aerodynamic Effect of Heavy Rain on Airplane Performance

Microburst Escape Sensitivity to Lift and Drag



The Aerodynamic Effect of Heavy Rain on Airplane Performance

Outline

- Review of heavy rain airfoil tests
- Development of heavy rain aerodynamic model for a twin-jet transport
- Performance analysis with heavy rain effects
- Numerical simulation of wet microburst encounter
- Summary of Results & Future Needs

The Aerodynamic Effect of Heavy Rain on Airplane Performance

Summary of Results

- The reduction in maximum lift capability and stall angle, as well as the increased drag of heavy rain, can substantially reduce climb performance
- Heavy rain can critically impair an airplane's ability to escape from an otherwise recoverable wind shear encounter
- The drag rise associated with heavy rain has the greater effect on wind shear recovery performance than the loss of lift

The Aerodynamic Effect of Heavy Rain on Airplane Performance

Future Needs

- This analysis was based on a limited data set and broad assumptions
- Need further testing of sub-scale and full-scale airfoil sections to determine scaling effects and flow mechanics
- Need sub-scale full configuration test
- Need information on heavy rain effect on engine performance

Estimate of Heavy Rain Performance Effect - Questions and Answers

Q: JOE YOUSSEFI (Honeywell) - Your data shows that the stall margin is reduced by approximately 2 degrees at landing flap configurations to levels on the order of 2.5 degrees. Does this represent adequate margin under turbulent conditions?

A: DAN VICROY (NASA Langley) - I can't answer that, I don't know. I would certainly think that you would raise a caution flag when your margin has been reduced to about half. I don't know how the stick shaker angle of attacks are established and whether or not they account for a margin for turbulence. Like I said, I'd raise a caution flag in any case.

Q: JOE YOUSSEFI (Honeywell) - Should the training aid guidelines be revised relative to operation at stick shaker prior to accumulation of additional heavy rain data?

A: DAN VICROY (NASA Langley) - I'd have to say no. We just don't know enough yet to make those kind of changes. When you look at the data base that the training aid was developed with compared to the data base we've developed in the heavy rain research, we just do not know enough yet about heavy rain to make those kind of decisions.

Session VII. 2nd Generation Reactive Systems

-

Session VII. 2nd Generation Reactive Systems

N 9 1 - 2 4 1 8 3

Status of Sundstrand Research
Don Bateman, Sundstrand

STATUS
of
Windshear R and D
at
Sundstrand Data Control, Inc.
17 October, 1990

Windshear Detection Status

- 2nd Generation Detection System is Here
- 3rd Generation Detection System is in Work
- Look-Ahead is in Research and Development

SECOND GENERATION DETECTION

IMPROVE RATIO OF:

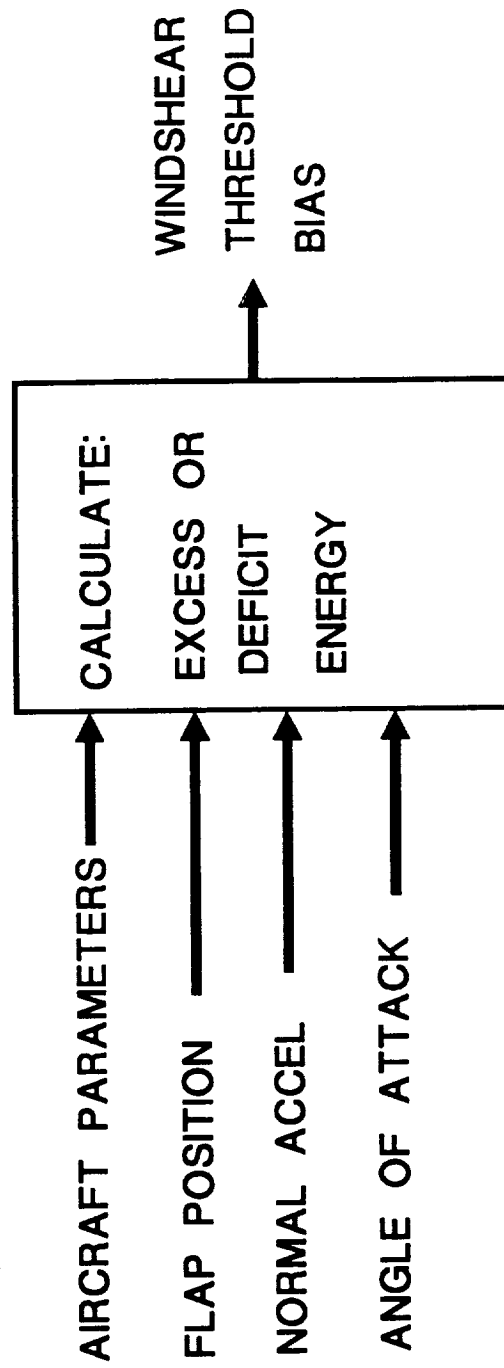
USEFUL ALERTS

UNWANTED ALERTS

- Q-BIAS
- GAMMA BIAS
- TEMP BIASES
- MANEUVERING FLIGHT
MODULATION
- ALTITUDE MODULATION

— CERTIFIED 1988 ! —

Q - BIAS



- REDUCES UNWANTED ALERTS FOR APPROACH INTO HIGH SURFACE WIND WHEN AIRCRAFT HAS HIGH ENERGY
- SENSITIZES SYSTEM WHEN ENERGY IS LOW

TEMPERATURE BIASES

LAPSE RATE IMPROVES USEFUL ALERT TIME

TEMPERATURE VALUE REDUCES UNWANTED ALERTS

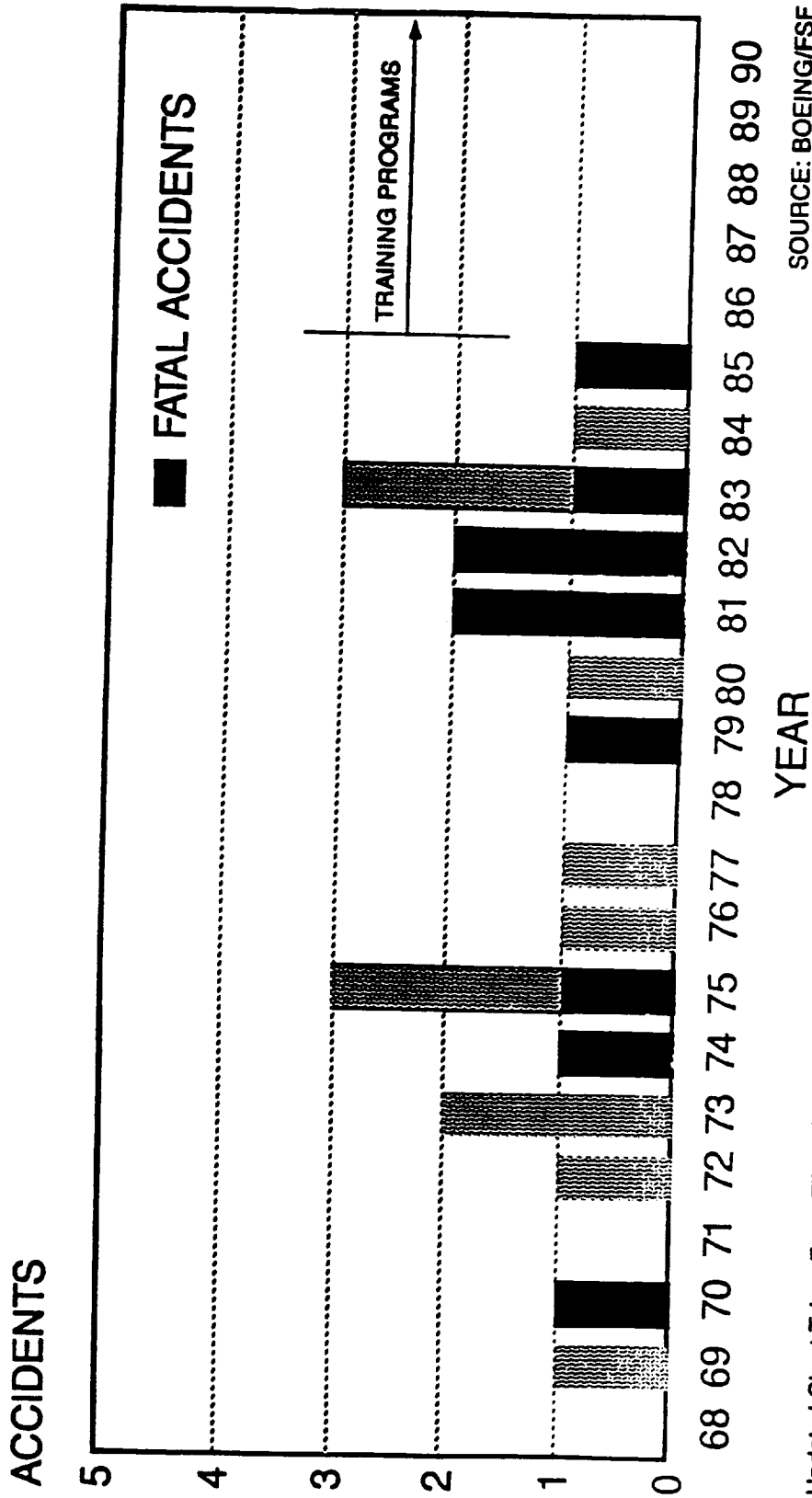
CURRENT SYSTEM PERFORMANCE

- **VALID WARNINGS ARE OCCURRING WORLDWIDE**
- **CREWS ARE RESPONDING PER APPROPRIATE PROCEDURE**
- **RATE OF UNWANTED WARNINGS IS LESS THAN 1 IN 3500 SEGMENTS**
- **WINDSHEAR "CAUTION" (POSITIVE SHEAR) $> F = -0.1$ ARE PROCEEDING NEGATIVE SHEARS BY 10 TO 15 SECONDS**
- **PREDICTIVE SENSORS WILL AUGMENT POSITIVE SHEAR DETECTION**
- **TEMP. LAPSE RATE BIAS IS PROVIDING 3 - 5 SECONDS IMPROVEMENT IN WARNING TIME**

Windshear

WORLDWIDE COMMERCIAL JET FLEET

88-04188, IAG 1801/88-JAH



SOURCE: BOEING/FSF

Updated Chart Taken From Flight Safety Foundation,
42nd IASS, Athens, 1989, Page 33.

attle Post-Intelligencer

ICE

SYLVIA / Nicole Hollander

Hi folks, this is your pilot... You know, we could have elected to Equip this plane with that new-fangled stuff that measures wind shear, but we thought you'd rather we put the money into upgrading the food.

Bon Appetit!



© 1990 BY NICOLE HOLLANDER

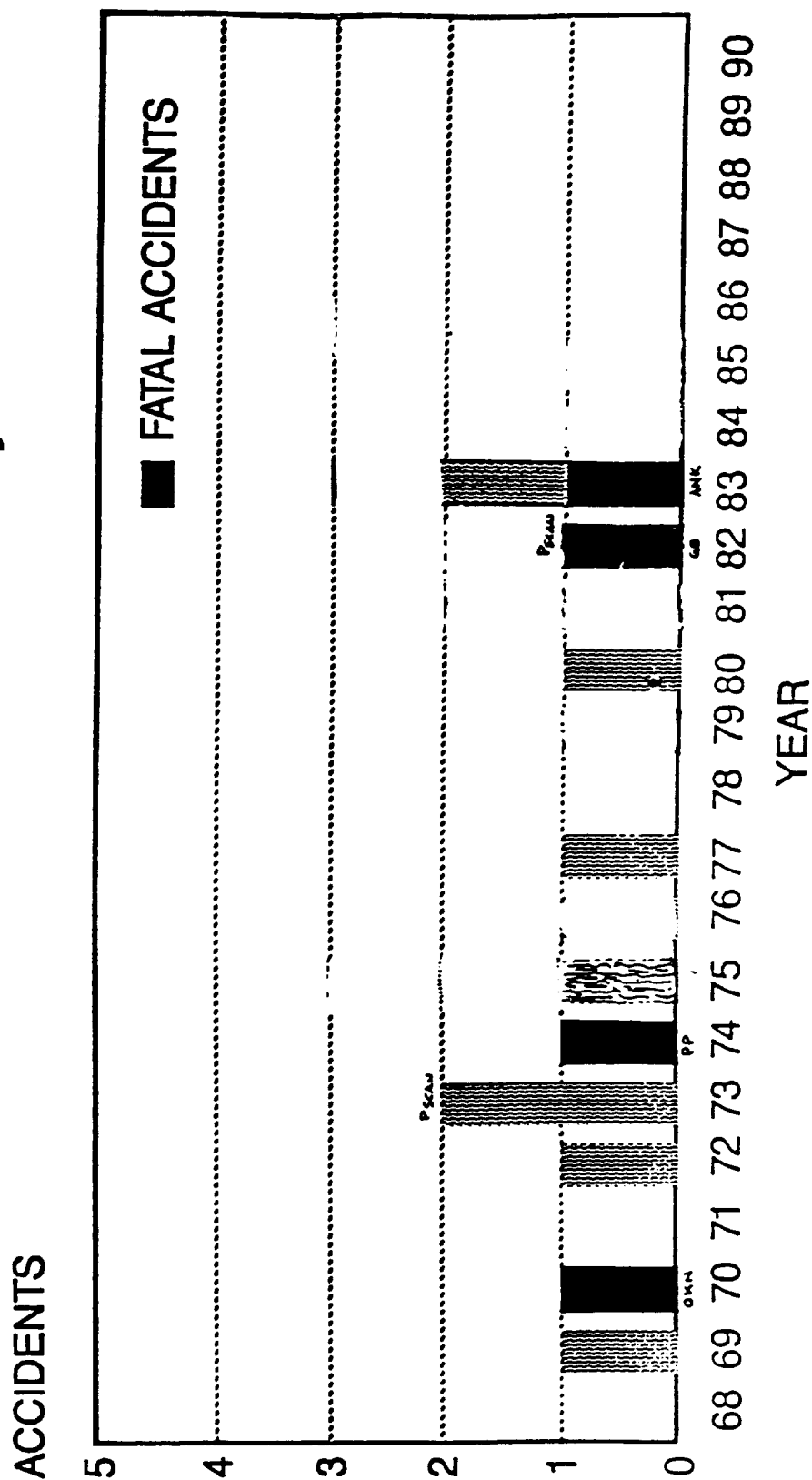
Sylvia appears Tuesday through Sunday in The Inner

-- That because of the effectiveness of our pilot training programs

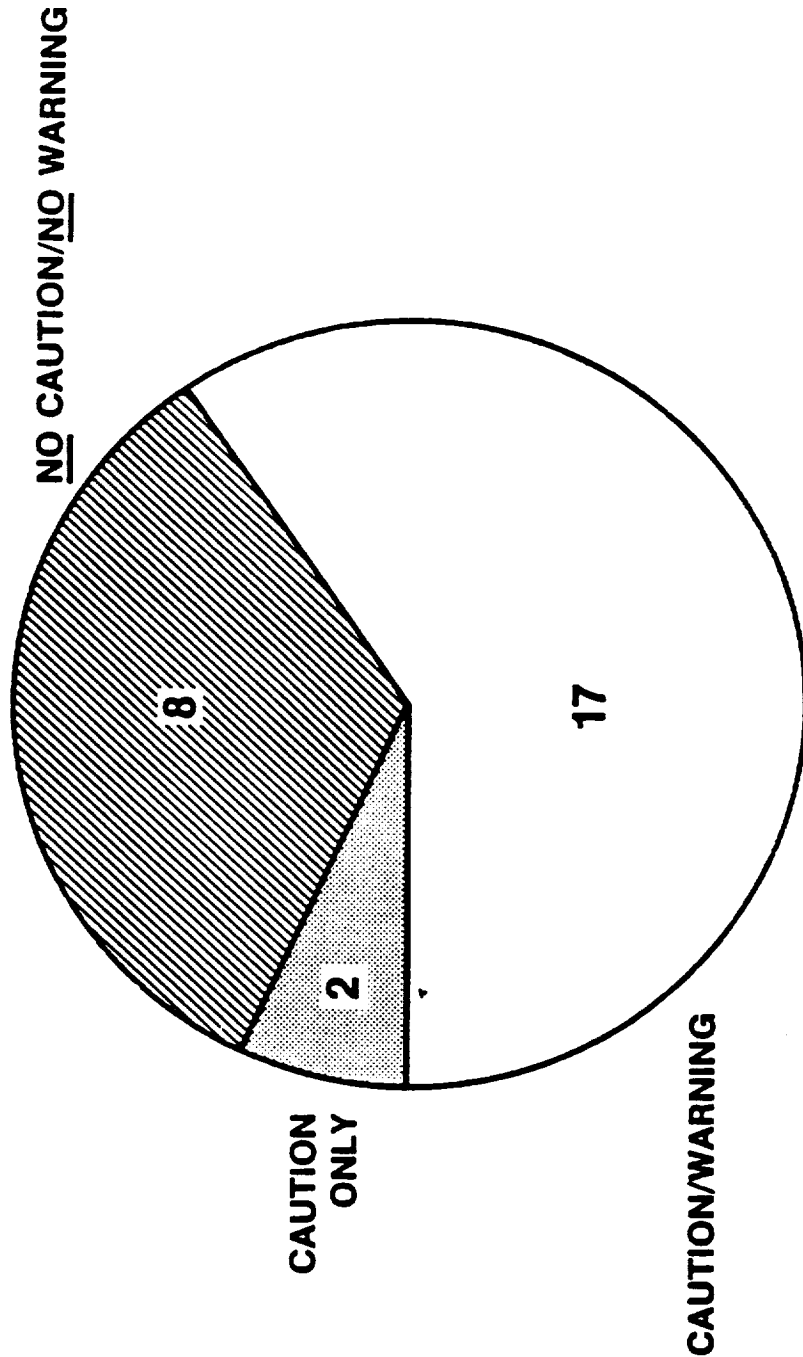
Third Generation Windshear Detection

Windshear

Accidents with no Warning For Current Detection Systems

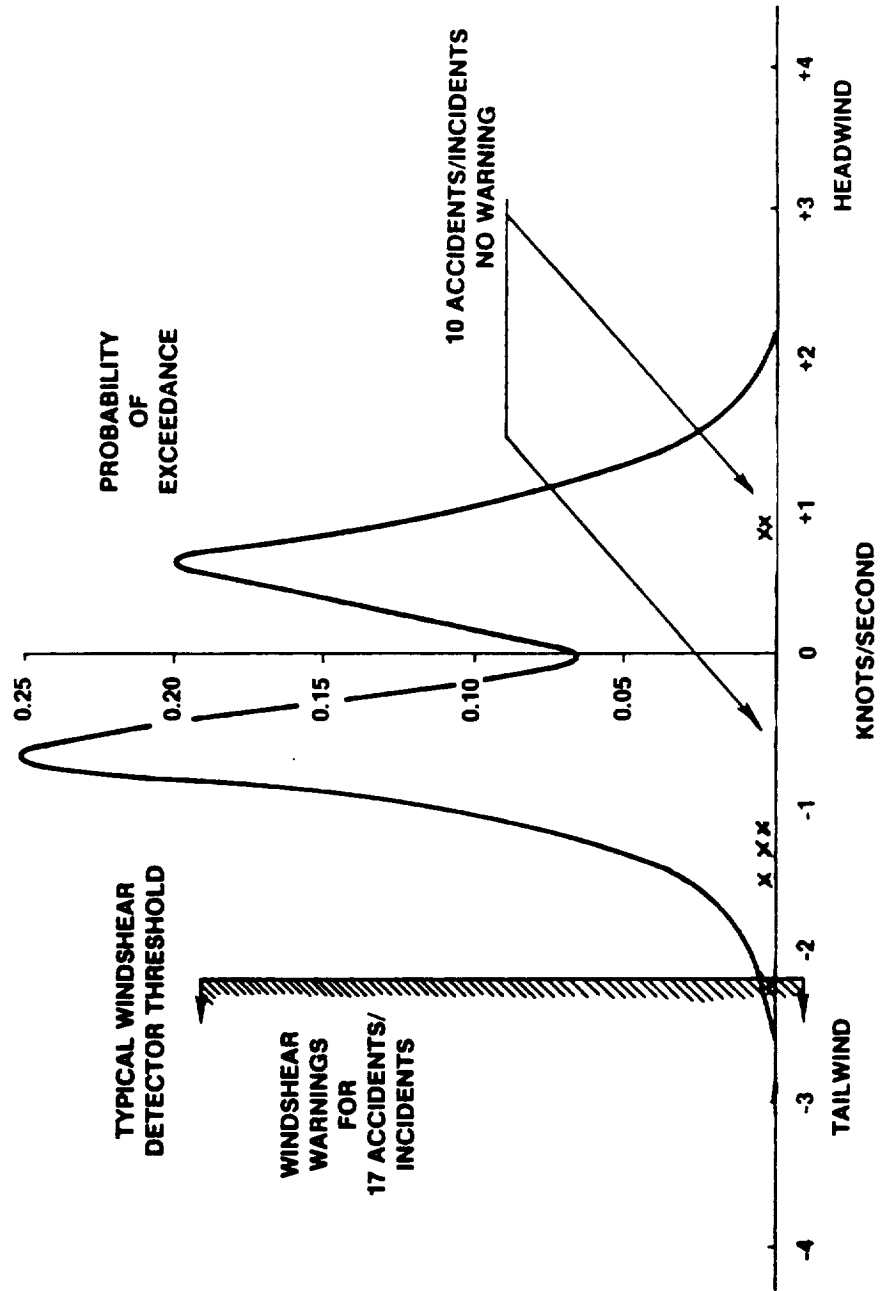


Effectivity of Second Generation Windshear Systems



27 WINDSHEAR RELATED ACCIDENTS/INCIDENTS
 (NATIONAL ACADEMY OF SCIENCES DATA BASE)
 1 MARCH 1964 - 28 JULY 1982

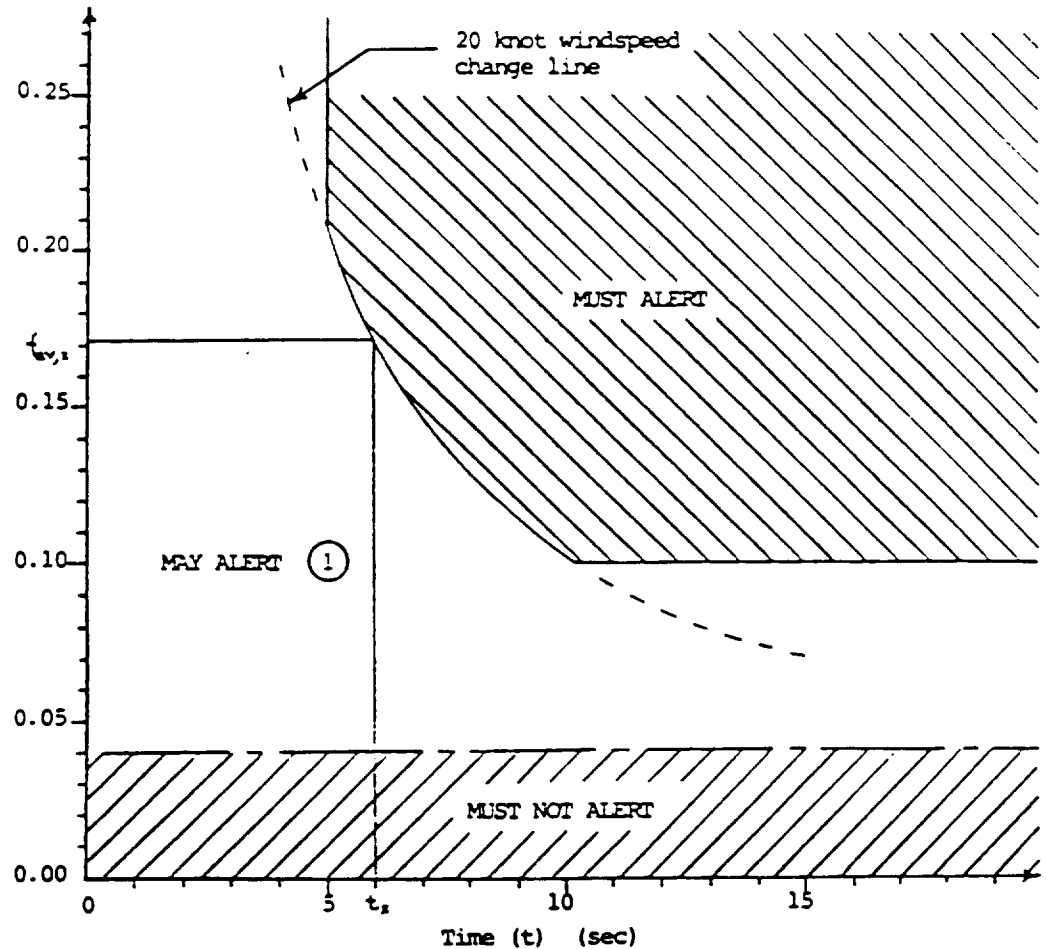
Windshear Threshold



Accident Examples Where Windshear Was A Contributory Cause and The Estimated Windshear Values Are Less Than TSO-C117 Warning Requirements, or the Aircraft Performance Capability.

-
- Okinawa DC-8 -1.2 Kts/Sec for 12 Seconds
 - Pago Pago B707 -1.3 Kts/Sec for 10 Seconds
 - Boston DC-10 +0.8 Kts/Sec for 15 Seconds
 - Ankara B727 +0.8 Kts/Sec for 36 Seconds
 - Dade-Collier DC-8 -1.5 Kts/Sec for 10 Seconds
- + Increasing Energy Windshear

FIGURE 1
SHEAR INTENSITY CURVE



$f_{w,x}$ = average shear intensity to cause a warning at time t_x (resulting in a 20 knot windspeed change, bounded as shown; applies to horizontal, vertical, and combination shear intensities)

$$= \frac{\int_0^{t_x} f(t) dt}{t_x} \quad \text{whereby } f(t) = \text{instantaneous shear intensity at time } t$$

- ① A nuisance warning test utilizing the Dryden turbulence model and a discrete gust model are conducted independently from alert threshold tests to verify the acceptability of potential nuisance warnings due to turbulence or gusts.

Flight Path Profile

DC-10-30
BOSTON, MASS.
17 DECEMBER, 1973

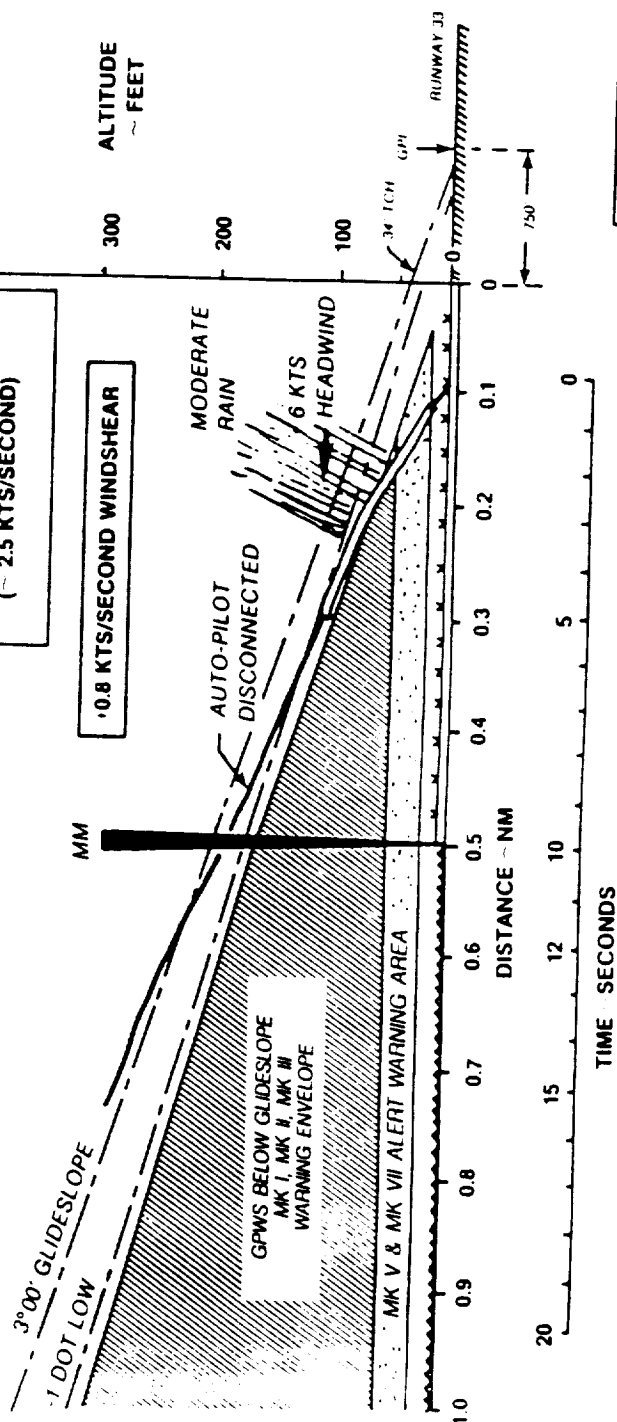
NOTES

Circumstances Flight 833 scheduled flight
Auto-coupled ILS approach to
175 feet with tail to headwind shear
Auto-throttles left engaged
Visual transition at 175 feet
in moderate rain
3x 3/4 mile visibility, fog, moderate rain
3007 - 41/38 79 97 RVR 3500
15 43 EST
Aircraft Destroyed \$21.5 million
3 seriously hurt 13 injured out of 168

118 KTS TAILWIND

NOTE:
NO WINDSHEAR CAUTION
OR WARNING FOR CON-
VENTIONAL WINDSHEAR
DETECTION SYSTEMS
(~ 2.5 KTS/SECOND)

0.8 KTS/SECOND WINDSHEAR



NO GPWS INSTALLED
NO WARNING FOR
MK I, MK II, MK III
IF INSTALLED

NO GPWS INSTALLED
NO WARNING FOR
MK I, MK II, MK III
IF INSTALLED

CURRENT WARNING

FLIGHT PATH PROFILE

B-707-300B
Pago Pago, American Samoa
31 January 1974

NOTE:

Circumstances: ILS Approach. Encountered micro burst—macro burst in rain at night and hit 3600 feet short of runway at 23:40 local time.

Weather: 16 @ 40 @ 110 @ 10 miles

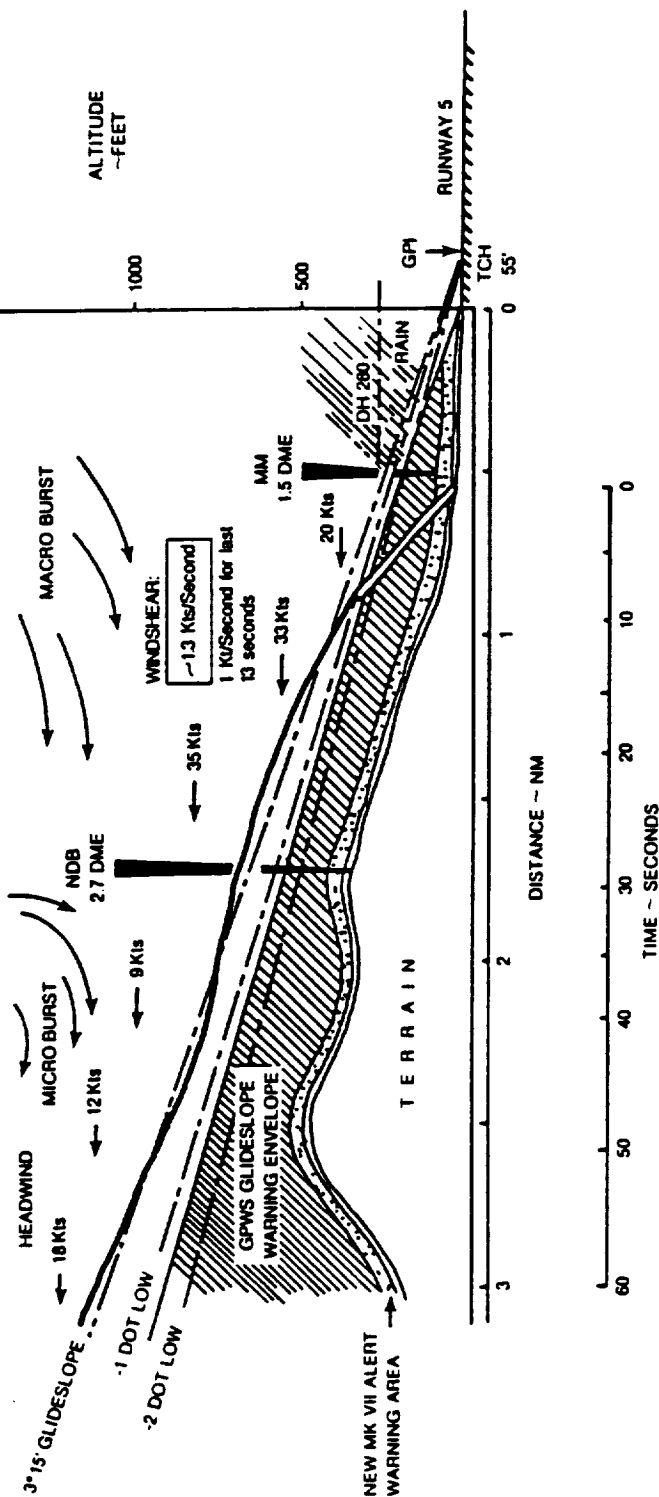
Wind 030/20 kts 25 gust. Light rain. Heavy rain shower near.

Loss: Aircraft destroyed \$5.5 million
 97 fatalities of 101 on board
 \$20 million liability.

NOTE:

NO WINDSHEAR WARNING
 FOR CONVENTIONAL WINDSHEAR
 SYSTEMS (App. 2.5 Kts/Second)

CAUTION ONLY



WIND DATA = FUJITA

MK V & MK VII WARNING

"SNKRAIE"

"GLIDESLOPE"

"GLIDESLOPE"

"SNKRAIE"

MK I

"GLIDESLOPE"

CURRENT WARNING
 SYSTEMS

Flight Path Profile

DC-8-62

DADE-COLLIER, FLORIDA

10 MAY, 1977

90-258

NOTES
Circumstances
Pilot training accident
Auto coupled ILS approach to
150 feet Windshear
Missed approach initiated
in heavy to moderate rain
Airplane touched down short of
11:20 EDT
Weather
1115 EDT E15 3 T 76 36/02 29 84
1121 EDT E15 1 T 76 74 29/08 29 84
Loss
\$0.15 Million

NOTE:
NO WINDSHEAR CAUTION
OR WARNING FOR CON-
VENTIONAL WINDSHEAR
DETECTION SYSTEMS
(~2.5 KTS/SECOND)

-1.5 KTS/SECOND WINDSHEAR
For Last 10 Seconds

ALTITUDE
~ FEET

MM

1 DOT LOW

2° 50' GLIDESLOPE

HEADWIND

TAILWIND

IM

HEAVY RAIN

45 FEET

GPWS GLIDESLOPE
WARNING ENVELOPE

ALERT WARNING AREA

MK V & MK VII

3 DOT LOW

GPWS

12 ICH

RUNWAY 9

700'

1200'

0

0.1

0.2

0.3

0.4

0.5

0.6

0.7

0.8

0.9

1.0

DISTANCE ~ NM

TIME ~ SECONDS

20

15

10

5

0

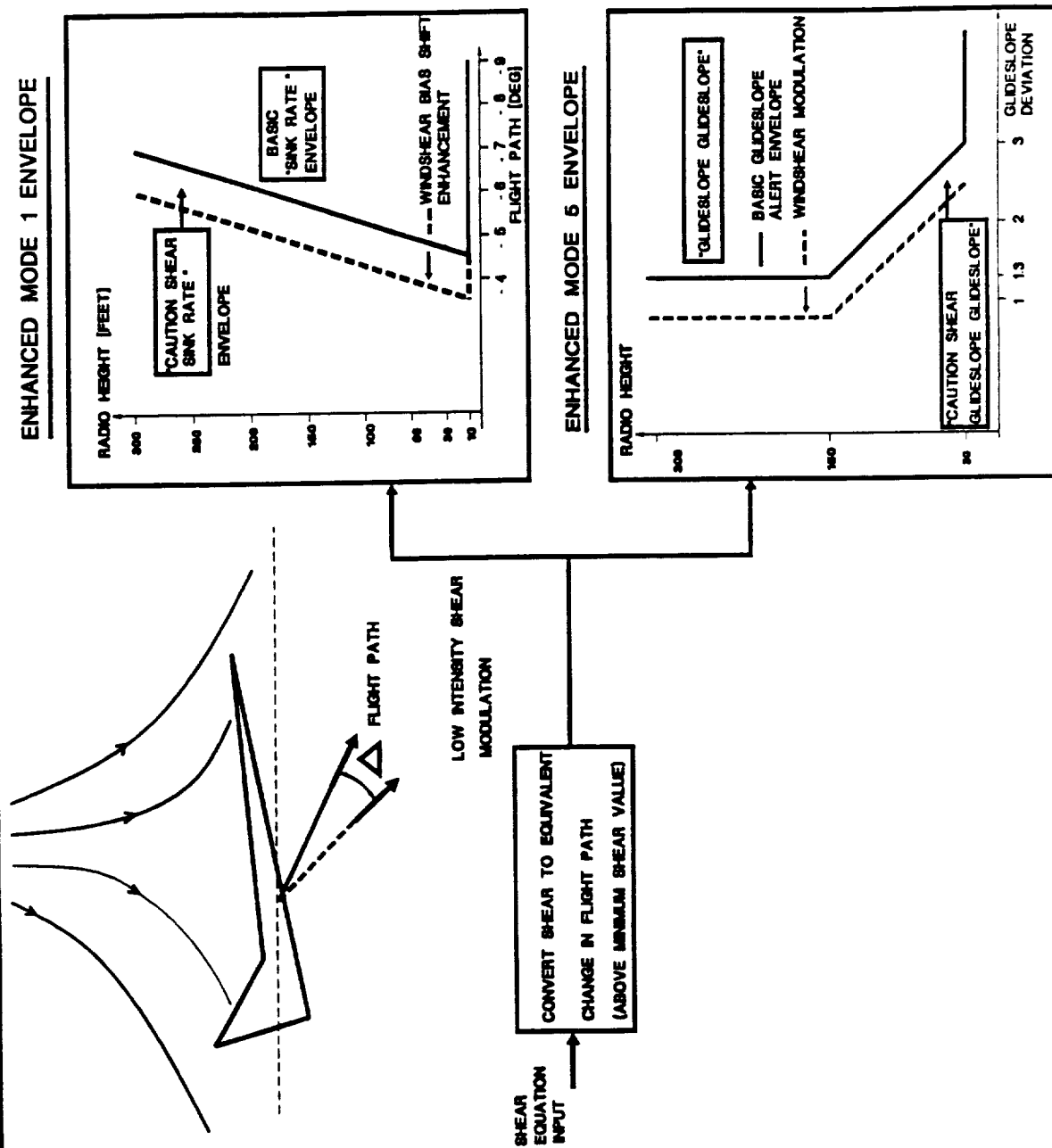
NO GPWS WARNING (MKI)
FOR INSTALLED SYSTEM

CURRENT WARNING
SYSTEM

MK V & MK VII WARNING

"SHRINKAGE"
"SHRINKAGE"
"GLIDESLOPE"

WINDSHEAR MODULATION OF MODES 1 AND 5



Circumstances:	ILS Approach. Encountered micro burst—macro burst in rain at night and hit 3800 feet short of runway at 2340 local time.
Weather:	16 ° 40 ° 110 ° 10 miles Wind 030/20 kts 25 gust. Light Heavy rain shower near.
Loss:	Aircraft destroyed \$5.5 million. 87 fatalities of 101 on board \$20 million liability.

Weather: 16 • 40 • 110 • 10 miles
Wind 030/20 kts gust 45
Heavy rain shower near.

Loss: Aircraft destroyed \$5.5 million
97 fatalities of 101 on board
\$20 million liability

Loss: Aircraft destroyed \$5.5 million
97 fatalities of 101 on board
\$20 million liability.

**NOTE:
NO WINDSHEAR WARNING
FOR CONVENTIONAL WINDSHEAR
SYSTEMS (App. 2.5 Kts/Second)**



Flight Path Profile

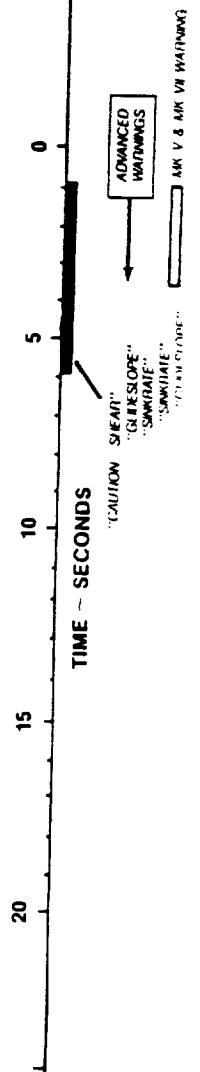
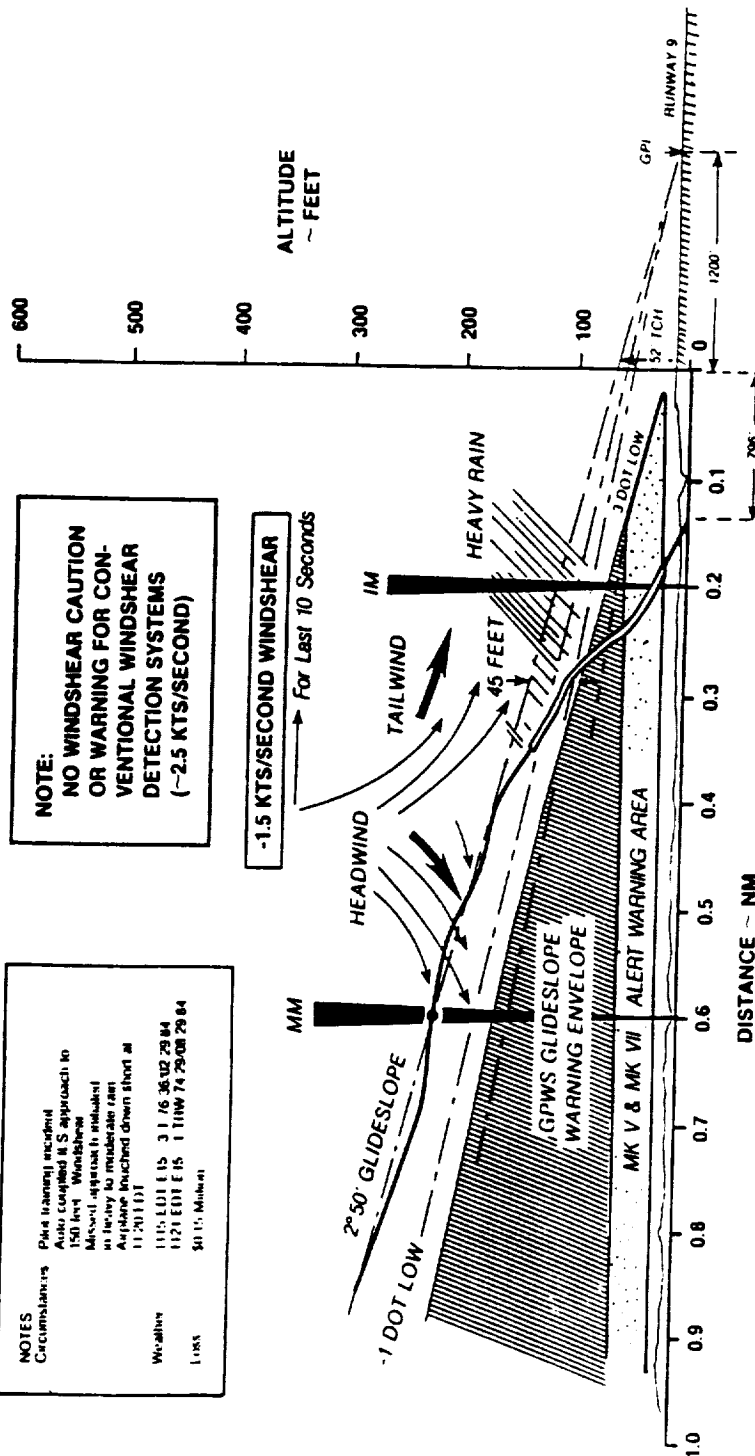
DC-8-62
DADE-COLLIER, FLORIDA
10 MAY, 1977

90-254

NOTES	
Circumstances	Pilot (training) incident Auto Coupled II S approach to 150 feet. Windshear missed approach to minimum in vicinity to moderate rain. Airplane touched down short at 11:20:11 DT
Weather	1115 L01115 3 1 16 1612 29 84 1121 E01115 1 11W 74 2908 29 84
Links	\$0 11, Miami

NOTE:
NO WINDSHEAR CAUTION
OR WARNING FOR CON-
VENTIONAL WINDSHEAR
DETECTION SYSTEMS
(~2.5 KTS/SECOND)

-1.5 KTS/SECOND WINDSHEAR
For Last 10 Seconds



NO GPWS WARNING (MKI)
FOR INSTALLED SYSTEM

ADVANCED WARNING
SYSTEMS

ADVANCED
WARNINGS

MK V & MK VI WARNING

THIRD GENERATION SYSTEM

- **USE WINDSHEAR COMPUTATION TO AUGMENT FLIGHT PATH AND TERRAIN ALERTS**
- **MODULATION OF ALERT THRESHOLDS BASED ON WIND/TERRAIN DATA BASE**
- **INCORPORATE WINDSHEAR/TERRAIN ALERT ENHANCEMENTS FROM PREDICTIVE SENSOR DATA**

Status of Sundstrand Research - Questions and Answers

Q: JOHN MCCARTHY (NCAR) - Are you aware of a Cuban Allusion 62 fatal accident? Havana, Cuba, September, 1989. There was 125 killed. Departure profile similar to Pan Am 759. The Cuban Civil Aviation Authority blamed (1) microburst, (2) crew training, (3) pilot actions. So the record is not clean since 1985.

A: DON BATEMAN (Sundstrand) - The chart I presented did not include any Soviet Union, Eastern bloc countries or Cuba. To me, this illustrates that the value of having an open society of nations where people trade back and forth accident information. As everyone knows in this room it was very difficult to get any information at that time, back in the 60s, the cold war, which really meant anything. Obviously if we put the Cuban and Russian and the other countries on the chart, we would probably have a continuing accident profile all the way across. Again I say the training programs, the education, avoidance, has really paid off. It's paying off everywhere in the world and I'm very proud that a lot of it came from the United States. I should say that since 1988 things are really changing. Mr. Gorbachev, who got the Nobel Prize yesterday, has really helped change that. Cuba still is very, very difficult, so close to us, yet so far in communicating with each other. Even Mr. Gorbachev hasn't been able to convince that openness that we need.

Q: PAUL KELLY (21st Century Technology) - What is the logic behind a wind shear alerting system that simply tells the crew somewhere in the vicinity is a wind shear? Without qualitative and quantitative data on the shear characteristics? Is not the only logical approach to crew alert some format that indicates the nature of the shear, its relevant position in respect to that aircraft as well as information on advisable maneuvering options? What's the good of spending money on any alerting system that does not address these three factors?

A: DON BATEMAN (Sundstrand) - Well, I wish we could give the pilot pictures. I think the speakers yesterday talking about the TDWR data transmittal to the airplane and displaying that, that adds another breadth to this, for the pilot to be able to really see what's going on out there. But this is nothing new. You have to start somewhere. I believe when a wind shear warning is given, the pilot is not asked what the picture is, or what the characteristics of the shear are, he is asked to leave. Perhaps with time maybe we'll get the pictures that the pilot really needs to see to help. I myself believe in not treating the pilot like a monkey, but to give him some information.

PAUL KELLY (21st Century Technology) - A very relevant adjunct to that question was as we saw this morning, sometimes a shear or the focal point of a microburst is not lined up with the longitudinal axis of the aircraft and it can be such that if the aircraft resorts to standard evasive maneuver by going on to standard missed approach path for that airport, it could very well end up putting himself into a tail wind, which of course will have the maximum danger. So, what is so important I believe, is that pilot needs to have some idea with regard to the physical characteristics of the microburst because standard evasive action could lead to him getting into a more dangerous situation which he would otherwise avoid if he had some information that made him realize that factor.

TERRY ZWEIFIL (Honeywell Sperry) - Yes, ideally that's what we would have. There would be some kind of situational display. Unfortunately there is 3000 commercial airplanes out there who have no capability to do that. The second point is, the reactive type systems are not predictive. That is, they only detect shears when you are in them. So it's going to be almost moot in terms of what part of the shear that you're in. It will either say you are in a shear or it will not. It's all one red light that comes on and says, "wind shear,

wind shear, wind shear." The standard guidance procedure, no matter who's system you're looking at, in terms of roll, is to keep the wings level. Therefore, we are never instructing the pilot to turn one way or the other where he might in fact turn into the shear. Actually the real reason we do that is to keep the drag on the airplane down. So unless you just happen to have a very bad day and you just happened upon the shear just as it moves across as you're coming into it, you could in fact get into a worse condition. But the reactive systems, as they're designed today, have no way of anticipating what that is. Like I say, in the future we hope to change all of that and that's why we have all of these forward looking guys with the TDWRs and LLWAS and those sort of things. But for right now, we need to protect the airplane population that's out there without any of these display capabilities, which even if we could generate the display, we have no where to put it. So they're kind of at the mercy right now of a simpler system.

Session VII. 2nd Generation Reactive Systems

N 9 1 - 2 4 1 8 4

Temperature Lapse Rate as an Adjunct to Wind Shear Detection
Terry Zweifil, Honeywell Sperry

TEMPERATURE LAPSE RATE

AS AN

ADJUNCT TO WINDSHEAR DETECTION

**TERRY ZWEIFEL
HONEYWELL, INC.**

TEMPERATURE LAPSE RATE AS AN ADJUNCT TO WINDSHEAR DETECTION

**TERRY ZWEIFEL
HONEYWELL, INC.**

ABSTRACT

As airborne windshear detection systems evolve, an increasing sophistication is required to assure more reliable and timely detection of hazardous windshears. As part of an on-going study by the University of Oklahoma and Honeywell, Inc., several meteorological parameters are being examined to determine if measurable atmospheric conditions can improve windshear detection devices.

Lapse rate, the temperature change with altitude, shows promise as being an important parameter in the prediction of severe windshears. It is easily measured from existing aircraft instrumentation, and it can be an important indicator of convective activity including thunderstorms and microbursts. This presentation briefly reviews the meteorological theory behind lapse rate measurement and describes an FAA certified system that is currently implemented in the Honeywell Windshear Detection and Guidance System.

LAPSE RATE AND MICROBURSTS

- THERE IS A SUBSTANTIAL BODY OF EVIDENCE INDICATING A CORRELATION BETWEEN TEMPERATURE LAPSE RATE (THAT IS THE CHANGE IN TEMPERATURE WITH ALTITUDE) AND THE PROBABILITY OF MICROBURST FORMATION.
- THIS RELATIONSHIP WAS FIRST DISCUSSED BY FERNANDO CARACENA OF ERL. SUBSEQUENT ANALYSIS OF THE DALLAS ACCIDENT SUBSTANTIATED HIS FINDINGS.

DRY ADIABATIC LAPSE RATE

- A MEASURED LAPSE RATE LESS THAN A DRY ADIABATIC LAPSE RATE (-3 DEG C/1000 FT) OVER A DEEP LAYER INDICATES AN UNSTABLE, CONVECTIVE ATMOSPHERE IN WHICH THUNDERSTORMS AND THUS MICROBURSTS CAN BE SPAWNED.
- THE OTHER REQUIRED INGREDIENT IS SUFFICIENT ATMOSPHERIC MOISTURE TO PRODUCE PRECIPITATION.
- CURRENT AIRCRAFT INSTRUMENTATION IS SUFFICIENT TO MEASURE LAPSE RATE, BUT CANNOT MEASURE MOISTURE DIRECTLY.

WET VERSUS DRY MICROBURSTS

▪ THE NATIONAL WEATHER SERVICE, SOUTHERN REGION, HAS FOUND THAT MICROBURSTS OCCURRING IN TEXAS THROUGH MISSISSIPPI OCCUR WHEN THERE IS A LAYER OF NEARBY DRY ADIABATIC LAPSE RATE EXTENDING UPWARD AT LEAST 6000 FEET FROM THE SURFACE.

▪ IN THE DENVER AREA, THIS LAYER IS USUALLY 8000 FEET OR MORE.

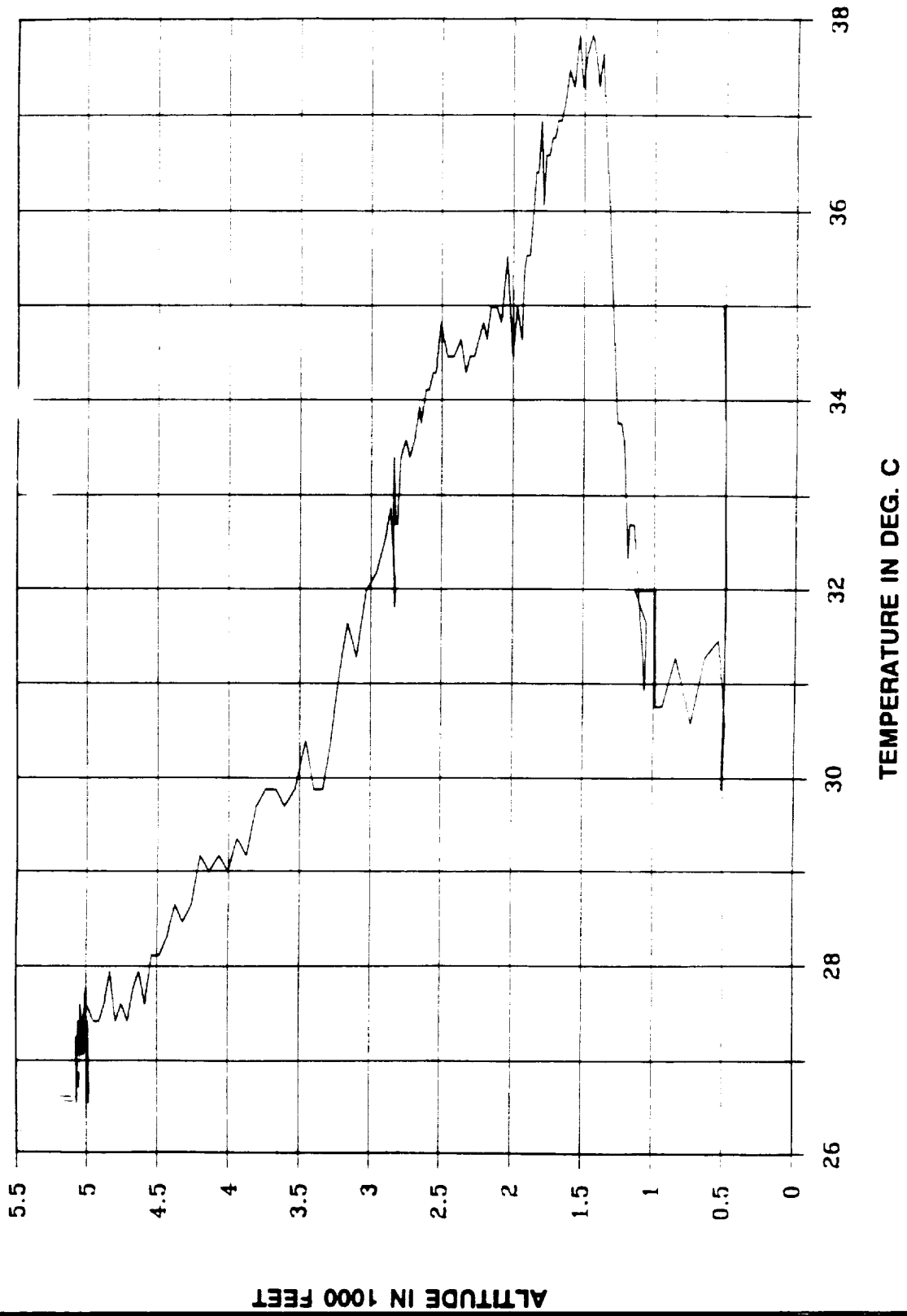
FERNANDO CARACENA, PERSONAL CORRESPONDENCE

CONVECTIVE ACTIVITY

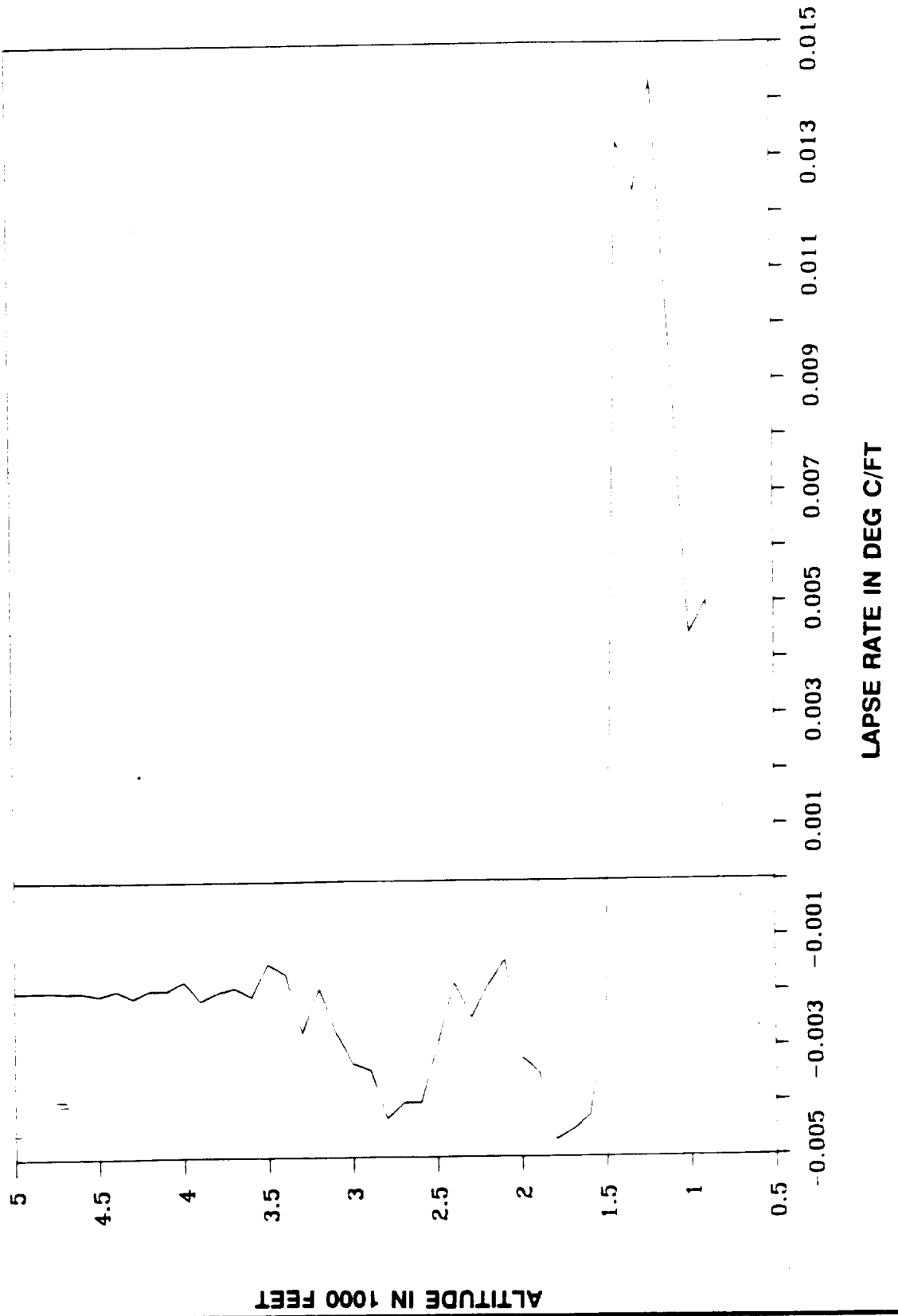
- THE IDEA THAT A DRY ADIABATIC LAPSE RATE (OR LESS) CAN PRODUCE THUNDERSTORMS AND TURBULENCE IS NOT A NEW ONE.
- "CONVECTIVE PHENOMENA ARE DETERMINED BY THE TEMPERATURE-HEIGHT CURVE, THE THICKNESS OF THE UNSTABLE LAYER, AND THE ALTITUDE OF THE CONDENSATION LEVEL", A PILOT'S METEOROLOGY, C.G. HALPINE, 1953.
- SINCE CONVECTIVE ACTIVITY IS OFTEN ASSOCIATED WITH TURBULENCE, LAPSE RATE MEASUREMENTS MAY ALSO BE USEFUL IN WARNING OF IMPENDING ROUGH AIR.

TEMPERATURE VERSUS ALTITUDE

DALLAS ACCIDENT

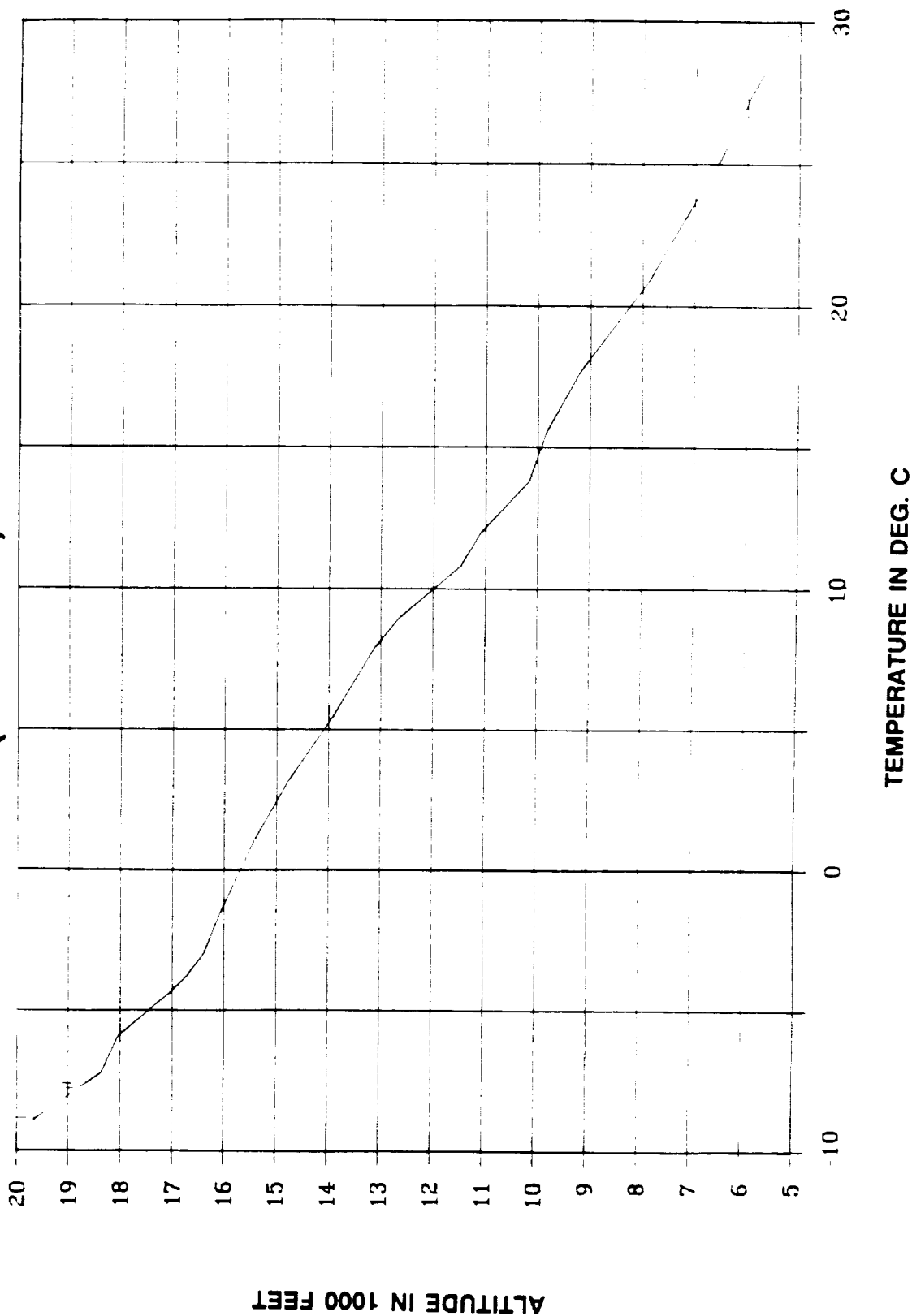


LAPSE RATE DALLAS ACCIDENT



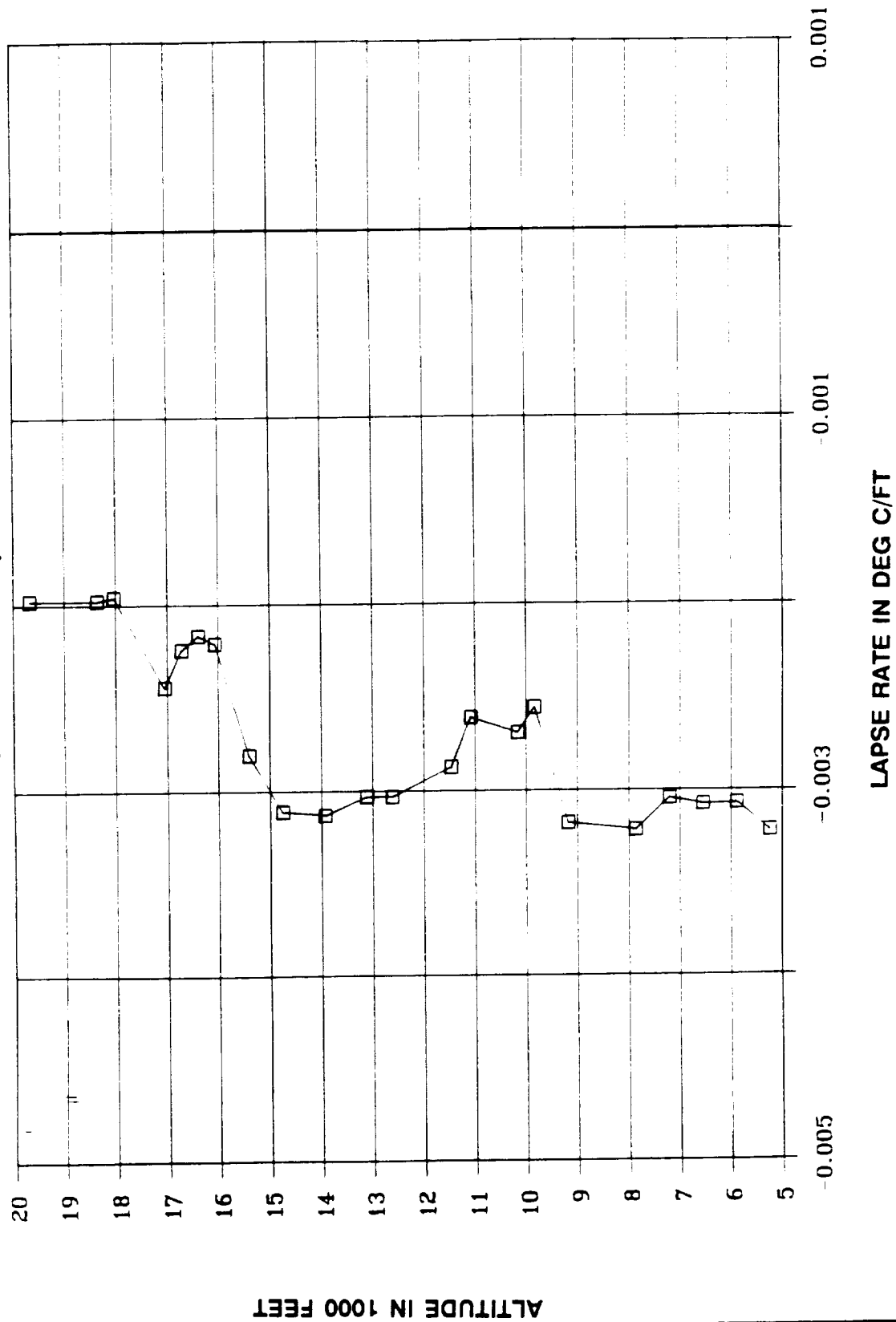
DENVER 11 JULY 1988

1404 MDT (2004 UTC) SOUNDING



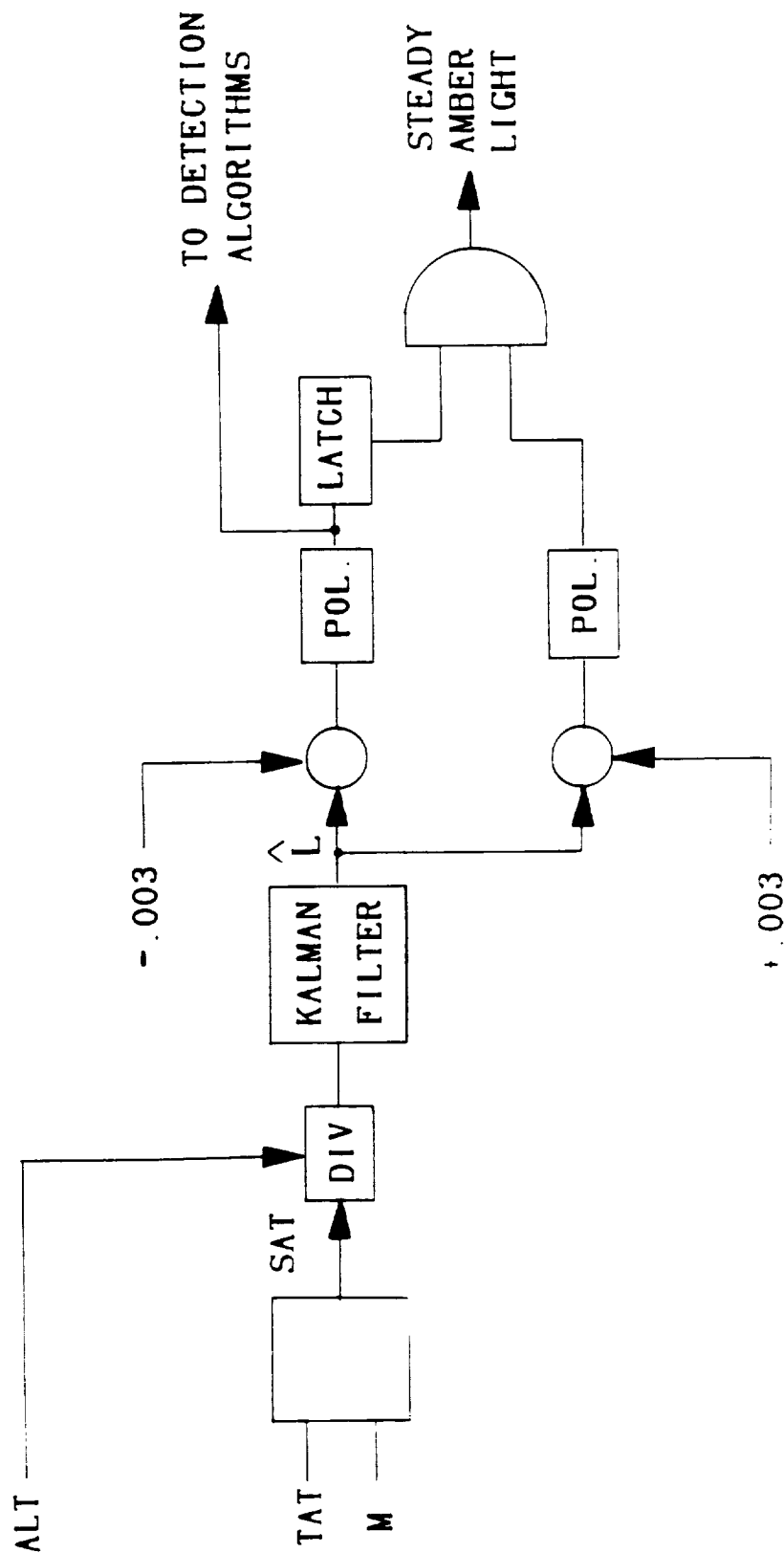
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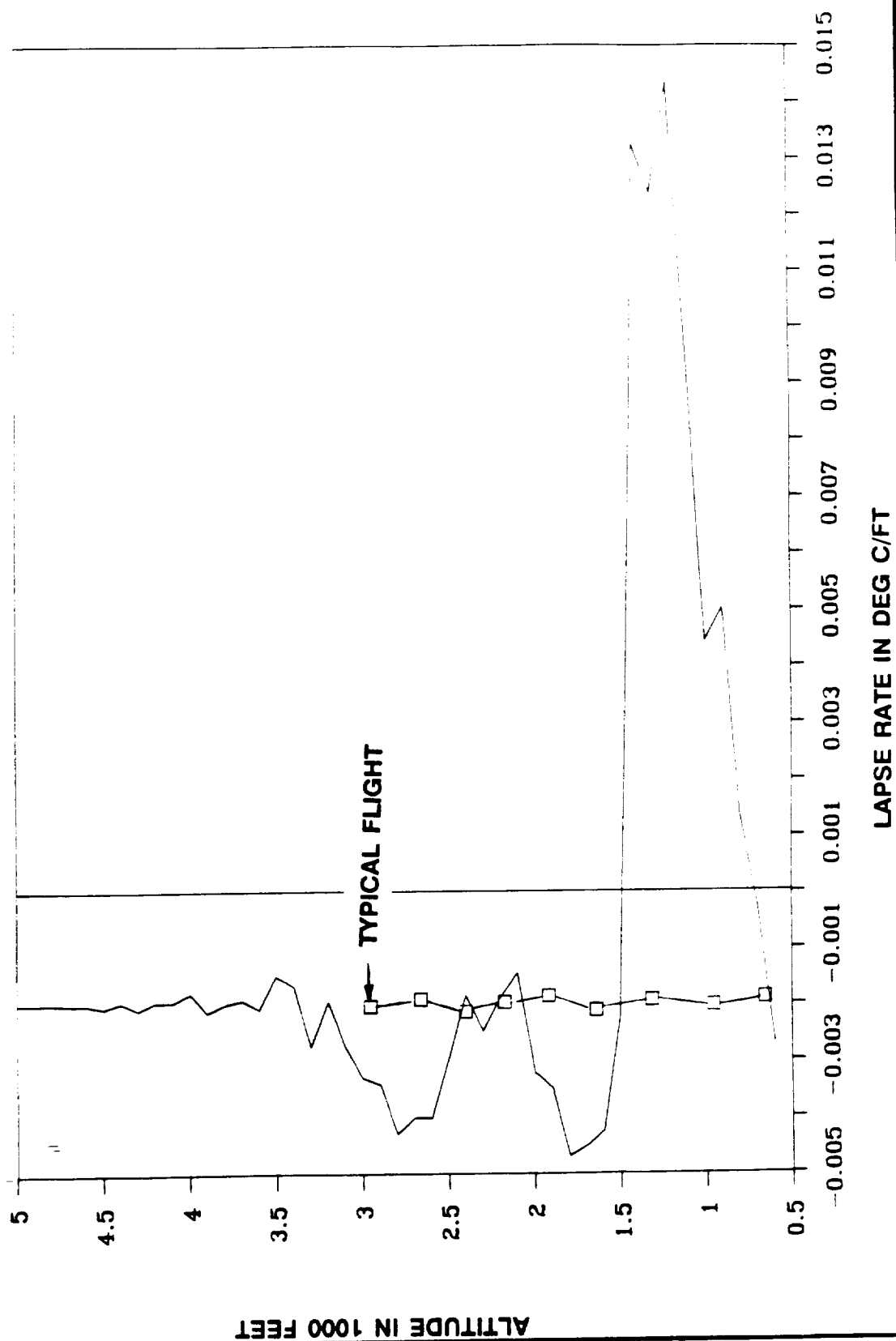
LAPSE RATE MEASUREMENT

SIMPLIFIED BLOCK DIAGRAM

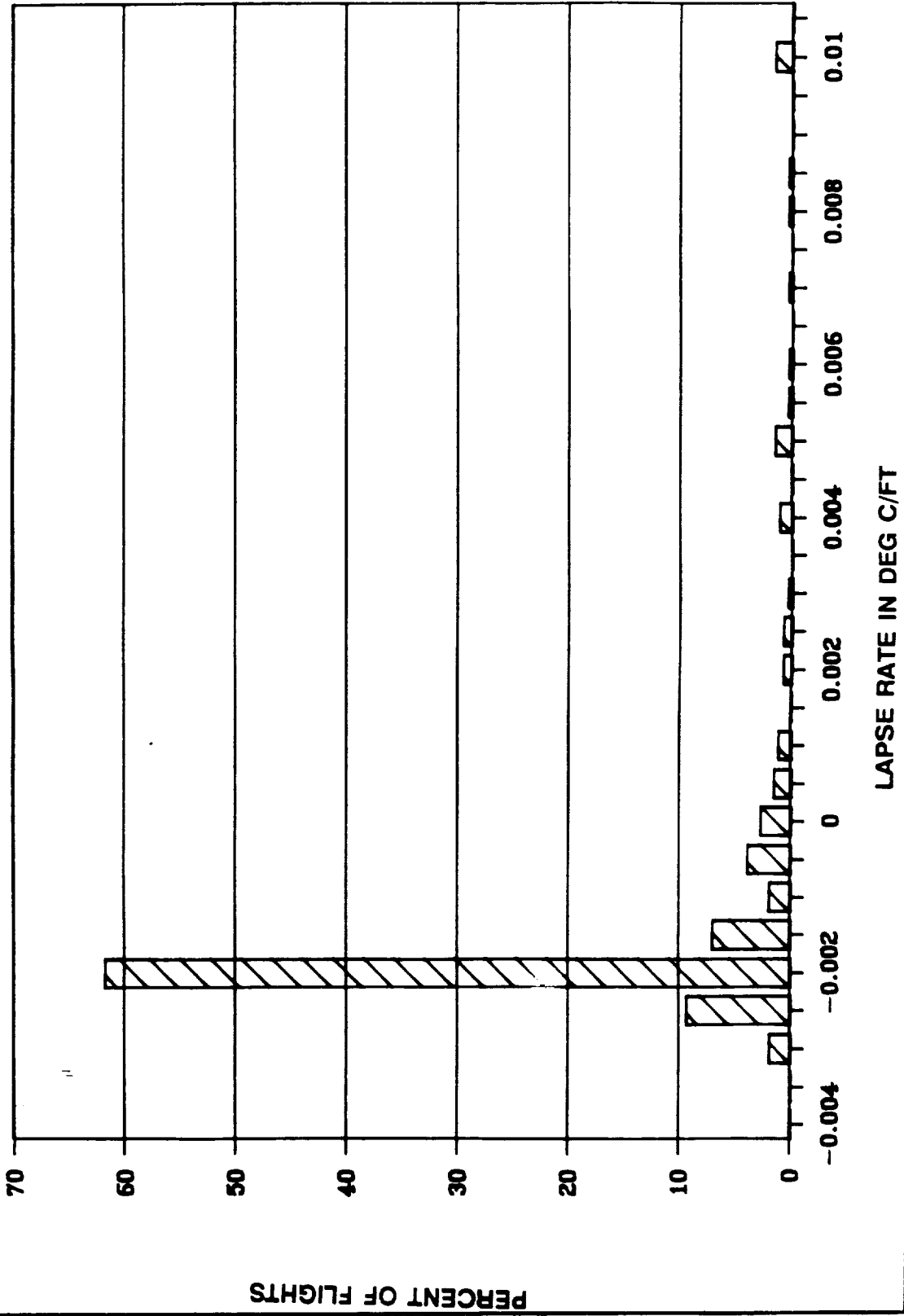


PATENT 4,947,165

LAPSE RATE COMPARISON TYPICAL FLIGHT VS. DALLAS ACCIDENT



LAPSE RATE EXTREMA



CONCLUSIONS

- LAPSE RATE MEASUREMENTS CAN BE SUCCESSFULLY UTILIZED TO DETECT THE OCCURRENCE OF CONVECTIVE ACTIVITY AND THUNDERSTORM ENVIRONMENTS.
- LAPSE RATE BY ITSELF CANNOT BE USED TO DETECT MICROBURSTS RELIABLY. AT BEST, IT INDICATES THE PROBABILITY OF A MICROBURST OCCURRENCE.
- LAPSE RATE CAN BE USED TO MAKE REACTIVE SYSTEMS MORE "INTELLIGENT", HENCE PROVIDING ADDED ASSURANCE THAT A DANGEROUS SHEAR HAS OCCURRED.
- LAPSE RATE MAY BE A GOOD INDICATOR OF LOW LEVEL TURBULENCE.

CURRENT STATUS

- THE LAPSE RATE ALGORITHM HAS BEEN FAA CERTIFIED AND IS CURRENTLY OPERATIONAL IN THE HONEYWELL WINDSHEAR COMPUTER.
- GIVEN THAT A DRY ADIABATIC LAPSE RATE IS DETECTED FOLLOWED BY A VERY POSITIVE LAPSE RATE, A STEADY AMBER LIGHT IS ILLUMINATED AS A CAUTION TO THE FLIGHT CREW, INDICATING A POTENTIALLY UNSTABLE AIRMASS CONDITION.
- THE DETECTION OF A DRY ADIABATIC LAPSE RATE IS ALSO USED TO ALTER THE THRESHOLDS OF THE BASIC WINDSHEAR DETECTION ALGORITHMS.

FUTURE DEVELOPMENT

- LAPSE RATE MEASUREMENTS ARE CURRENTLY BEING INVESTIGATED AS A MAJOR COMPONENT OF A WINDSHEAR EXPERT SYSTEM.
- KELVIN DROEGEMEIER OF THE UNIVERSITY OF OKLAHOMA IS SIMULATING MICROBURSTS WITH VARYING ATMOSPHERIC CONDITIONS, INCLUDING LAPSE RATE, FOR HONEYWELL.
- USING THESE DATA, HONEYWELL IS PROGRAMMING AN EXPERIMENTAL EXPERT SYSTEM THAT NOT ONLY USES ATMOSPHERIC PARAMETERS, BUT ALSO OVERSEES THE INPUTS OF BOTH REACTIVE AND LOOK-AHEAD SENSORS.

Optimal Guidance during a Windshear Encounter

An aircraft caught in windshear experiences a dangerous loss of lift. An application of optimal control theory has identified the best strategy for surviving such conditions, a strategy now implemented in the Honeywell Windshear Computer.

Terry Zweifel
(Sperry Commercial Flight Systems Division)
AZ75-N30D2: 602-869-2979

At six o'clock on the evening of August 2, 1985, Delta Air Lines Flight 191 was on final approach for a landing at Dallas-Fort Worth International Airport. A thunderstorm was forming near the north edge of the field, directly on the approach path to the active runway. Two other aircraft landed safely, but by the time Flight 191 reached the storm cell, it had built up to a dangerous intensity. Within the cell, the aircraft entered a region of severe windshear and began losing altitude. In spite of the crew's strenuous efforts to maintain control, the aircraft fell below the prescribed glide slope and struck the ground more than a mile short of the runway. The crash killed 134 people on board the aircraft as well as the driver of an automobile on a highway just outside the airport.

The loss of Flight 191 is the most recent of 28 aircraft accidents since 1964 caused by the meteorological effect called windshear. The accidents have resulted in 623 deaths and 237 injuries. In the past decade, about half of all commercial-aircraft accidents have been related to windshear. All of them have happened during takeoff or landing maneuvers.

To prevent such accidents in the future, the best policy is doubtless to avoid flying into regions of windshear. To this end, various sensor systems, such as Doppler radars, have been developed to detect windshear conditions near airports, so that pilots can

be warned to delay takeoffs and landings until the danger passes. But ground-based detectors can never be perfectly accurate and reliable. Inevitably, an aircraft will occasionally stray into a windshear region. The question then becomes how best to get out of the predicament.

My colleagues and I at the Sperry Commercial Flight Systems Division have approached this question as a problem in optimal control. In other words, we have asked what control strategy should be adopted to maximize the chances of successfully flying through the windshear. We have discovered that the optimum strategy is in fact a simple one, which we have implemented in the Honeywell Windshear Computer. This instrument is now capable of detecting the presence of windshear and then either directing the pilot or commanding the aircraft's autopilot to follow the optimum escape path.

The Windshear Hazard

The term *windshear* refers to any situation where wind velocity varies sharply from point to point. Windshears can be caused by a number of atmospheric phenomena, such as weather frontal systems, but the most lethal form of windshear is called a microburst. Events of this kind, which are always associated with thunderstorms, were discovered by T. Theodore Fujita of the University of Chicago. A microburst is a column of rapidly

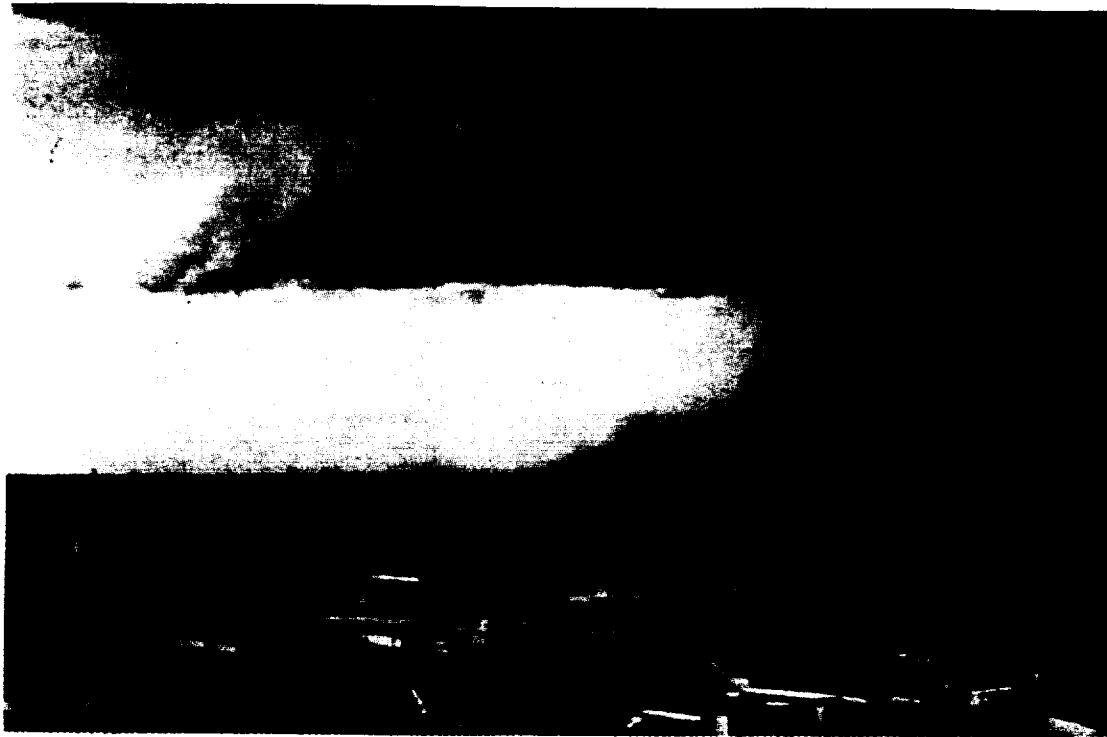
descending air, which fans out radially as it nears the ground, like the stream from a faucet splashing into a basin (see upper illustration on page 112). A typical microburst is less than three miles across and lasts 15 minutes or less.

An aircraft attempting to traverse a microburst during takeoff or landing usually encounters a headwind first, followed by a downdraft and finally a tailwind. Contrary to what one might guess, it is not the downdraft that represents the greatest hazard to aviation but rather the tailwind. When the horizontal component of wind velocity shifts from a headwind to a strong tailwind, the effect is to reduce the craft's air speed; that in turn reduces lift. Loss of lift, of course, causes the aircraft to descend.

The corrective for the loss of lift is to increase the aircraft's angle of attack, or in other words to pitch the nose upward relative to the airstream. If the angle of attack exceeds a limiting value, however, the aircraft will enter an aerodynamic stall. The limiting value is called the "stick-shaker" angle, because a mechanical vibrator attached to the pilot's control column is activated at this point to warn of an impending stall. On a typical commercial jet transport the difference between normal angle of attack and stick-shaker angle is only about six degrees. Thus the range of control available for counteracting the effects of windshear is quite limited.

Scientific Honeywell

ORIGINAL PHOTO BLACK AND WHITE PHOTOGRAPH



THUNDERSTORM CELL spawns a microburst—a descending column of cold air—near Stapleton International Airport in Denver. The microburst is the dark area in the right half of the photograph. As it flares out in a radial pattern on reaching the ground, it creates severe windshear, or in other words a strong gradient in wind velocity. Windshear conditions encountered during takeoff and landing are the most serious weather hazards to

modern commercial aviation. Much effort has been put into detecting and avoiding windshear; the Commercial Flight Systems Division has developed an instrument that implements the optimum strategy for escaping a windshear. The photograph was made July 8, 1984, by T. Theodore Fujita of the University of Chicago and Wendy Schreiber of the National Center for Atmospheric Research.

Apart from the limited range of control, the natural dynamics of an aircraft create further difficulties in coping with windshear. Speed and altitude in an aircraft are closely coupled: If a windshear causes a loss of air speed, the aircraft naturally tends to pitch down (that is, decrease its angle of attack) and regain the speed at the sacrifice of some altitude. A loss of altitude, on the other hand, has the opposite effect: the aircraft tends to gain air speed as it descends, which increases lift and causes the aircraft to climb. The result of this continual exchange of potential and kinetic energy is a roller-coaster motion called a phugoid oscillation. It is an oscillation with a long period (typically 30 seconds), and in most aircraft it is poorly damped or even divergent (*see lower illustration on page 113*).

In normal flight the phugoid oscillation is suppressed by continually adjusting the angle of attack in order to maintain a zero rate of change in altitude or air speed. The adjustments can be made by the pilot through the control column or by an automatic flight-control system. In a windshear encounter, however, there may not be sufficient control latitude to arrest the phugoid motion, since the angle of attack may be near the stick-shaker limit. If the phugoid oscillation is not controlled, the altitude excursions can grow large enough to cause ground impact.

Given these aerodynamic constraints, the object of a windshear guidance law is to make optimum use of the available range of control and thereby to maximize the probability of survival. To achieve this goal, we

employed the methods of optimal control theory.

The Best Flight Path

The first and most fundamental rule for negotiating windshear conditions during the approach to landing is that no attempt is made to land the aircraft. Instead, the pilot initiates a go-around maneuver, increasing engine thrust to the maximum and adjusting angle of attack so as to establish a nonnegative rate of climb.

To determine the optimal guidance law for executing such a go-around maneuver, we simulated an aircraft's flight in windshear conditions. The simulation program, which ran on a personal computer, was adapted from one written by J. René Barrios. The original version had been used in the development of the Honeywell Per-

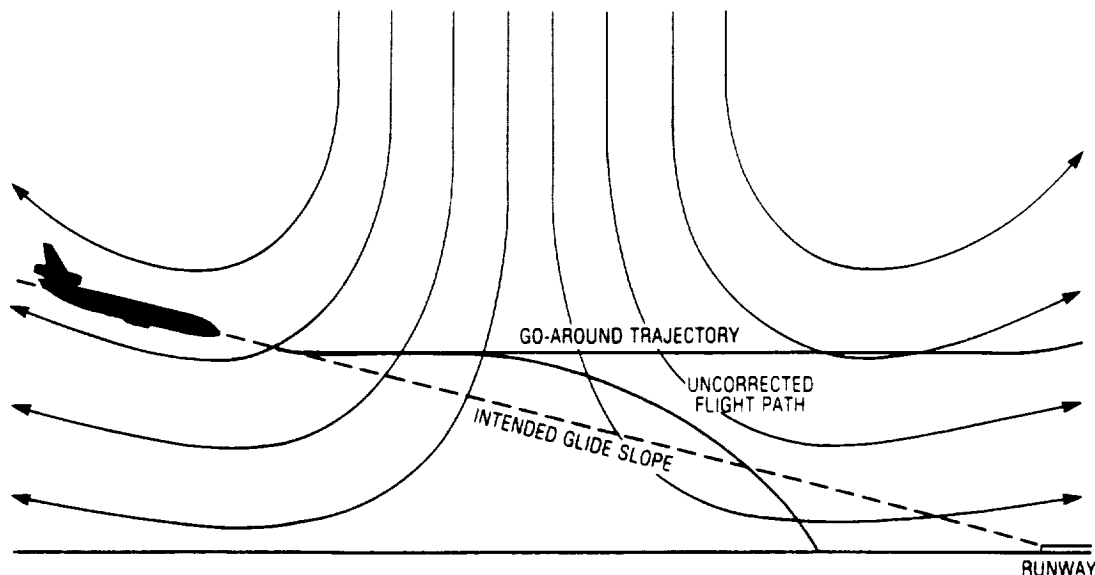
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formance Management System to determine the Mach number that yields minimum fuel consumption [see "Optimizing Aircraft Performance," by Sam Lidén, on page 101]. In our

studies of the windshear problem we modified the program to make the control variable angle of attack rather than Mach number. At each instant during a simulation the state of the

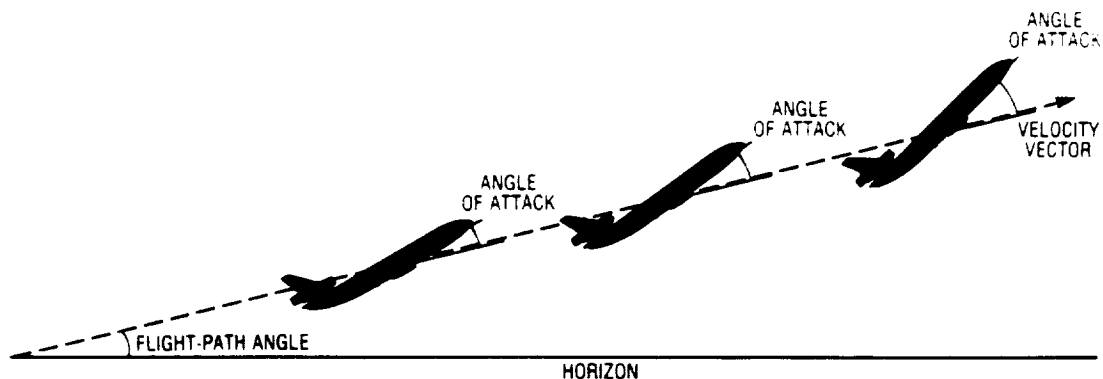
aircraft was defined by its altitude, air speed and distance travelled and by the wind velocity.

An interesting aspect of the problem was choosing criteria by which to



MICROBURST is a small-scale but intense meteorological phenomenon, seen only in conjunction with thunderstorms. The downdraft in a microburst can have a velocity of 40 knots or more, and the horizontal winds near the surface are even more violent, sometimes exceeding 200 knots. The high wind velocities, however, are not the principal hazard to aviation; the main threat comes instead from the rapid change in wind speed and direction experienced by an aircraft traversing the microburst at low altitude. In the diagram an aircraft encounters severe windshear

on final approach to landing. Initially, a headwind augments the craft's air speed and lift, so that it rises above the intended glide slope. But a steadily increasing tailwind then reduces both air speed and lift, so that the aircraft sinks and strikes the ground short of the runway. The recommended action in these circumstances is not to attempt a landing but rather to initiate a go-around maneuver. Optimal control theory has identified the best strategy for executing a go-around in windshear.



ANGLE OF ATTACK is the primary means of controlling an airplane's path during a windshear encounter. The angle of attack is the angle formed between an aircraft's axis and its direction of motion relative to the air mass. Increasing the angle of attack generates greater lift, but there is a limiting angle that cannot be exceeded or the aircraft will enter an aerodynamic stall. The limiting angle of attack is called the stick-shaker angle because a

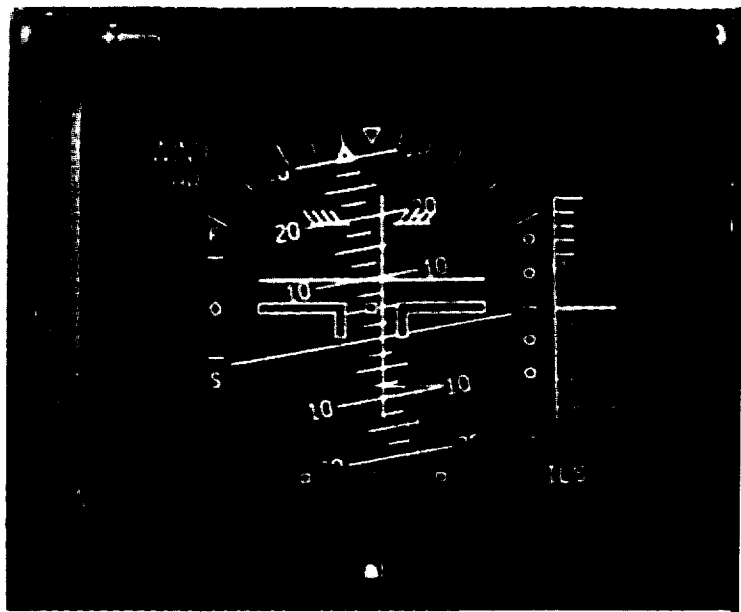
vibrator attached to the control yoke is activated at this point to warn the pilot of an impending stall. The difference between normal angle of attack and the stick-shaker angle is only about six degrees, which is all the latitude available for controlling flight in a windshear episode. The aim of the optimal control law is to make the most effective use of this limited range.

Scientific Honeyweller

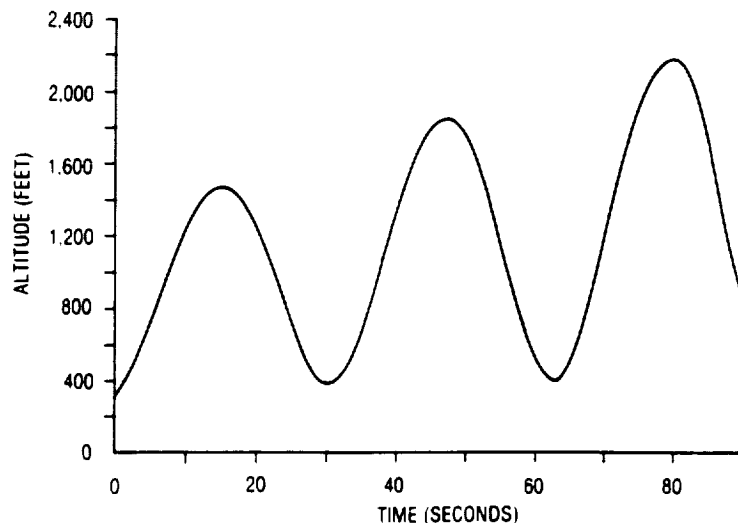
judge candidate control laws. In the early stages of the investigation we considered a number of possible criteria. For example, one approach takes as an ideal the flight path that would be followed during a go-around in the absence of windshear; then the optimal control law is the one that minimizes deviations from this path. Other criteria favor control laws that minimize the curvature of the flight path or the rate of change in altitude or that maximize ground clearance. We constructed grading schemes that incorporated various combinations of these factors. After a multitude of simulation runs, however, the correct criterion proved to be a simple one, although not necessarily an obvious one. To understand the motivation for this choice, it must first be observed that some windshears are so severe that an aircraft cannot traverse them no matter what control law it employs. We found that the optimal control law is the one that under such extreme conditions keeps the airplane airborne for the longest possible time.

What control law provides the maximum time aloft? The answer to this question also emerged from our simulations. It turns out that the best policy is to maintain level flight, or in other words to fly at a constant inertial altitude. There are two reasons this strategy works well. First, it maximizes the time available before the angle of attack must be increased to the stick-shaker limit in order to maintain altitude. Second, flying a constant altitude tends to damp the phugoid oscillation.

Other candidate control laws invariably call for climbing in the presence of windshear. The weakness of this strategy is that it diminishes air speed, and, as noted above, at a lower air speed angle of attack must be increased to maintain lift; thus the angle-of-attack margin available for control is quickly dissipated. Once the stick-shaker angle is reached, the aircraft is essentially uncontrollable. If the angle of attack is increased further, the aircraft will stall; conversely, if the angle of attack is decreased, the aircraft will rapidly descend. Even



COCKPIT FLIGHT DIRECTOR advises the pilot when windshear conditions have been detected and provides guidance on the best strategy for recovery. The warning "WIND SHR" in the upper left corner of the display flashes red to indicate the presence of a serious windshear. The large crosshair in the center of the display consists of vertical and horizontal command bars, which instruct the pilot on what action to take. At the left edge of the display is a scale bounded by the letters "F" (for "fast") and "S" (for "slow"). During takeoff and landing this scale indicates the aircraft's angle of attack, with the "S" mark representing the stick-shaker angle; thus the instrument shows the pilot how much control is available before the aircraft reaches the stick-shaker limit.



PHUGOID OSCILLATION complicates the task of flight control in windshear. The oscillation results from a natural coupling between air speed and altitude: If some perturbation causes an aircraft to lose speed, it will also lose lift and so will begin to sink. The descent, however, increases air speed and lift, inducing a climb. In most aircraft the phugoid oscillation has a long period (30 seconds or more) and is poorly damped or even divergent. In normal flight it is easily controlled by manual or automatic adjustments to the angle of attack, but in a windshear the angle of attack may have to be held at the stick-shaker limit. In that circumstance the fluctuations in altitude can grow until the aircraft strikes the ground. The graph records a simulation of an uncontrolled oscillation.

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holding the controls perfectly steady at the stick-shaker angle is not an attractive option. With no range of control motion to damp the phugoid oscillation, the aircraft begins a series of altitude excursions that inevitably result in ground impact.

The clear imperative emerging from our simulations was to maximize the time available before a pilot must resort to stick-shaker angle of attack in order to keep the airplane aloft. Actually, the theoretical maximum time is attained not in level flight but when the aircraft is allowed to descend slightly. Incorporating this strategy into a general control law does not seem prudent, however. After all, a windshear might be encountered at very low altitude, or features of the surrounding terrain, such as hills and tall buildings, might make descent hazardous.

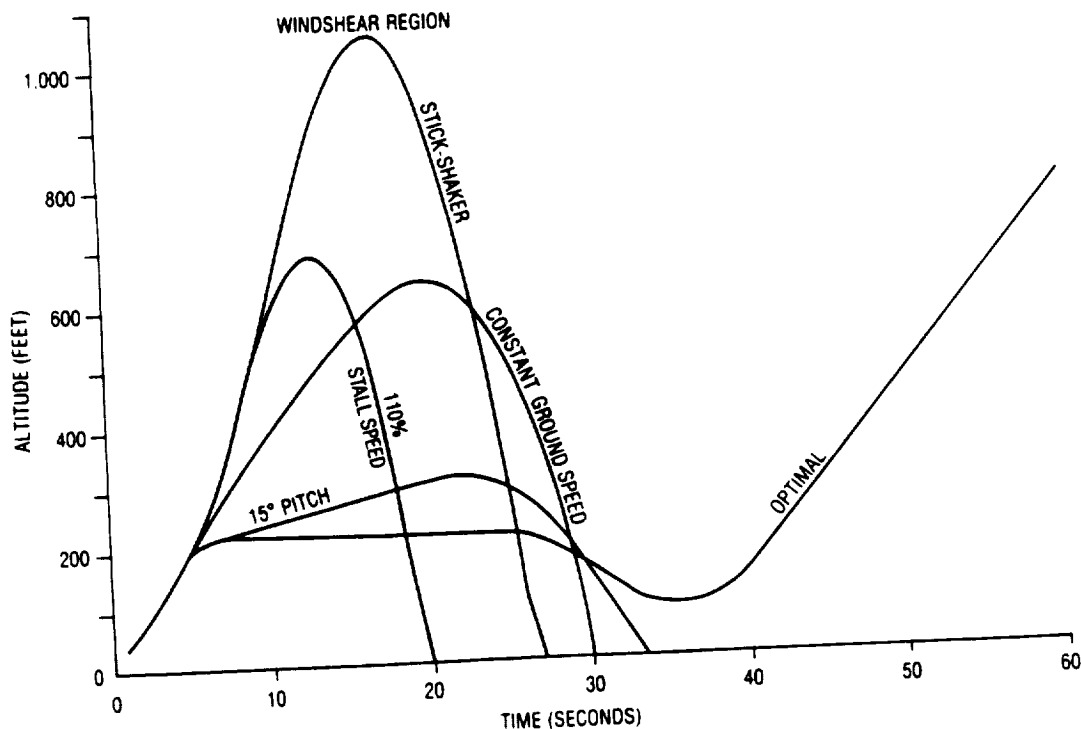
Other investigators have also explored the question of optimal guidance in windshear. For example, Angelo Miele of Rice University has applied numerical methods to the problem. Even though the methodology differs in the various studies, the conclusion is the same: the optimum practical guidance strategy for a pilot caught in windshear is maintaining level flight.

Simulation Results

The outcome of one series of simulations is shown in the illustration below. Here a typical commercial jet aircraft encounters a windshear shortly after takeoff, when it is at a height of about 200 feet. The tailwind develops about five seconds into the simulation run and increases at a rate of five knots per second; it ends after 23 seconds,

when the total change in wind velocity is 115 knots. This represents a severe windshear episode. In the crash of Flight 191, for comparison, the horizontal component of the wind shifted over a period of about 30 seconds from a 23-knot headwind to a 49-knot tailwind.

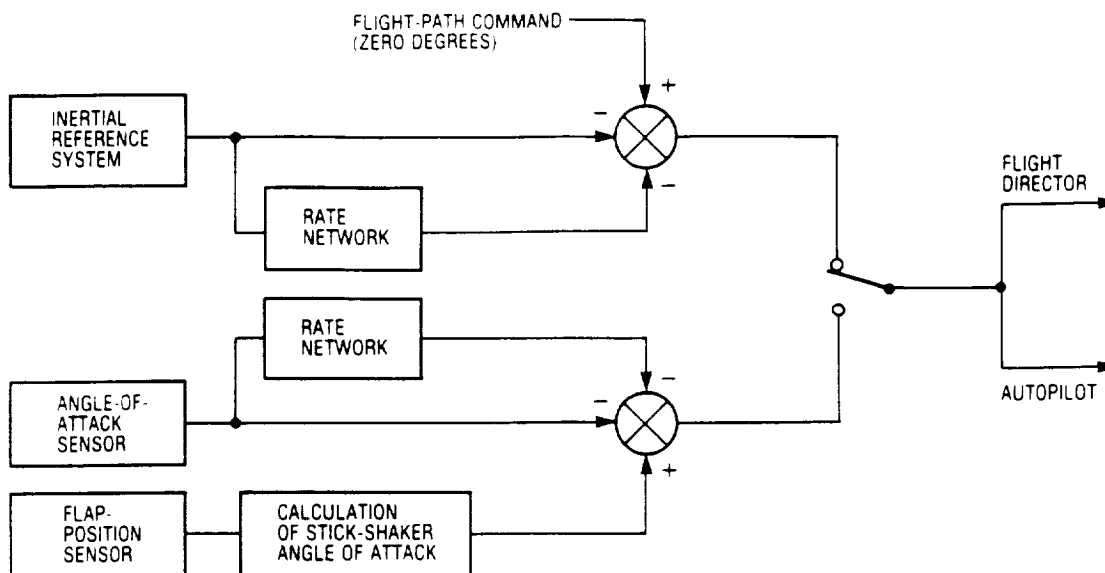
The simulation examines the effects of five control laws, each of which has been advocated at one time or another during the past decade as an appropriate response to windshear. The first strategy is to regulate angle of attack so as to maintain 110 percent of stall speed. The result is a steep climb, which cannot be sustained; after just 20 seconds the aircraft plunges back to earth. Holding the controls at stick-shaker angle of attack leads to an even more dramatic rise—the peak altitude is greater than 1,000 feet—and an



CANDIDATE CONTROL LAWS were tested by simulation on a personal computer. The simulated weather conditions included a tailwind beginning about five seconds into the run and increasing at a rate of five knots per second, then ending 23 seconds later. Four of the control laws tested had been recommended at one time or another as strategies for escaping windshear. Flying at 110 percent of stall speed, holding stick-shaker angle of attack or

maintaining a constant ground speed all produce a dramatic climb followed by a catastrophic plunge. When the aircraft maintains a 15-degree pitch angle, it remains aloft slightly longer. The optimal strategy of flying a constant inertial altitude—or in other words a zero-degree flight-path angle—is the only one that allows the aircraft to survive.

Scientific Honeywell



OPTIMAL CONTROL LAW has been implemented in the Honeywell Windshear Computer. When windshear is detected, the system continually regulates angle of attack in order to maintain level flight (a zero-degree flight-path angle) without exceeding the stick-shaker angle. The zero-degree commanded flight-path angle is compared with the actual angle, as measured by an inertial reference system; the rate of change in the angle is also included in the calculation to help damp fluctuations. The

difference between commanded and actual flight-path angle is an error signal that goes to a flight-director indicator on the pilot's instrument panel or to an autopilot that directly controls angle of attack. If the angle of attack reaches the stick-shaker limit, an auxiliary control network takes over, maintaining this maximum useful angle of attack (and thus maximum lift) without allowing the aircraft to stall.

equally catastrophic descent. Maintaining zero longitudinal acceleration, or in other words constant ground speed, keeps the craft airborne a few seconds longer.

The most effective of the nonoptimal strategies tested here is flying at a constant pitch angle of 15 degrees. This is the escape plan currently recommended by the Federal Aviation Administration for aircraft not equipped with windshear detection and guidance systems. If the simulated windshear had ended a few seconds sooner, the aircraft following the 15-degree strategy would have successfully crossed the danger zone.

The optimal strategy of maintaining constant altitude is the only plan that allows the aircraft to survive the simulated windshear episode. Even in this case it is not possible to stay aloft indefinitely. At about 25 seconds into the simulation run, the angle of attack has reached the stick-shaker limit and cannot be increased further; hence the aircraft begins to sink. If the windshear

had continued a few seconds more, the aircraft would have crashed.

Implementation

The optimal control law derived from our simulations and analyses has been implemented in the Honeywell Windshear Computer, an instrument developed in the early 1980's by the Sperry Aerospace & Marine Group and certified by the FAA in 1985. In its original form the windshear computer merely detected the presence of windshear, alerted the flight crew and provided an angle-of-attack reference the pilot could use in flying out of the danger zone. With the optimal control laws the computer can now offer more specific guidance to the pilot or can take over control of the aircraft, guiding it on the optimum flight path.

The computer detects windshear conditions by comparing signals from a number of inertial and air-data sensors. For example, one warning sign is a change in airspeed (as measured by a pitot probe in the airstream) that is not

matched by a change in inertial velocity (as determined by integrating the output of an accelerometer). Going beyond mere detection to active control does not require any additional inputs.

In its simplest form the control mechanism requires only one input: a signal representing the flight-path angle, or in other words the aircraft's rate of climb or descent. If the aircraft is equipped with an inertial-reference system, the flight-path angle can be measured directly by a system of gyroscopes and accelerometers. Otherwise, the angle of the craft's trajectory with respect to the air mass is calculated from air-data sensors and is then corrected for the effects of vertical and longitudinal winds. Regardless of the source of the information, it serves the same function. When the computer detects a windshear condition, the controller commands an inertial flight-path angle of zero degrees and compares this value with the actual angle. The difference is an error signal that indicates deviation from the optimum

flight-path angle. If the aircraft is under manual control, the error signal is supplied to the flight director, an instrument that guides the pilot to the correct control actions. Under autopilot control, the error signal is translated directly into movements of the elevator or other aerodynamic control surfaces.

The actual windshear control system is somewhat more complicated than this account might suggest (*see illustration on page 115*). In addition to the flight-path angle, the computer also considers the rate of change in this angle; including a rate term in the feedback loop helps to damp out rapid fluctuations and makes the aircraft more "flyable."

Another part of the control system takes over when level flight can no longer be sustained. As a rule, the controller will call for steadily increasing angle of attack during a windshear episode in order to avoid loss of altitude. This trend cannot be allowed

to continue once the stick-shaker angle is reached, or the aircraft will stall. A separate control loop is therefore included to monitor angle of attack. The stick-shaker angle, which depends on the position of the wing flaps, is continuously calculated and compared with the actual angle of attack. Whenever the actual angle exceeds the upper limit, the constant-altitude controller is switched off, and the airplane is held at stick-shaker angle of attack. Rate of change in the angle of attack is also included in the calculation as a damping and anticipatory factor. If the angle of attack is increasing rapidly, the rate term will prevent overshooting and a possible stall.

The control section of the windshear computer includes several further refinements. For example, filters and variable gain schedules improve flyability. The implementation of the control laws is now complete, and the system is operational in the Honeywell

Windshear Computer. Indeed, it has passed the ultimate test: it has provided guidance to successfully escape a real microburst encounter.

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Temperature Lapse Rate as an Adjunct to Wind Shear Detection Questions and Answers

Q: CARL YOUNG (Eastern Airlines) - How do you tie lapse rate technology with your zero gamma reactive system?

A: TERRY ZWEIFIL (Honeywell Sperry) - A quick word on what zero gamma means. That is really what we do when the shear is detected. We fly what is called an optimal flight path which we've shown through various studies, us and others, that flying a zero gamma relative to the earth gives you the optimal flight path. That is, it will keep you in the air longer than any other strategy. The lapse rate itself has really nothing to do with the guidance part of it other than sensitizing the system so that it gives you the wind shear quicker. The way the system works, when it detects a wind shear, says "wind shear, wind shear, wind shear", if you're in take off you automatically get the optimal guidance. If you are in approach, you do a missed approach technique, either slamming the throttle full forward or hitting the go around switches, either one will give you the automatic guidance. But the lapse rate itself really doesn't have anything to do at that.

Q: CARL YOUNG (Eastern Airlines) - If we're going to use an accelerometer based system to trigger a wind shear reactive system, how would you weight that versus lapse rate technology? Are you tending more to have lapse rate technology be predictive?

A: TERRY ZWEIFIL (Honeywell Sperry) - No, the lapse rate right now is not intelligent enough to handle the wind shear detection case. The only thing we can use it as is the probabilistic measure of wind shear, really microburst threats. It, in itself, will never replace the current reactive systems that you see today.

Q: PAUL ROBINSON (Lockheed) - From your presentation I got the impression that it was of the greatest importance to detect dangerous wind shears from microburst only. What precautions are taken to insure that dangerous shear from other sources, not microburst, are not overlooked by the dependents on lapse rate?

A: TERRY ZWEIFIL (Honeywell Sperry) - We never turn the system off with lapse rate measurements. It's simply an adjunct to what we're doing now. We'll change the thresholds slightly, not greatly. Without going into a great, elaborate thing to show you how actually we detect shears it's kind of hard to explain. The lapse rate is primarily used to sensitize for microbursts and the reason is that most of the wind shear accidents we have seen are in fact microburst caused. But we will still detect frontal shears, even terrain induced shears could set the system off.

Q: BOB OTTO (Lockheed) - What is the reduction in alert time when first generation reactive systems are coupled with temperature lapse rate measurement? That is, if the reactive system affords t seconds warning, then what increase to t does lapse rate measurements afford?

A: TERRY ZWEIFIL (Honeywell Sperry) - That's going to depend a lot, of course, on what particular shear model you use and what the lapse rate looks like. Let me give you an example, from Dallas you will get about 3 - 4 seconds quicker warning that you would have from a purely reactive system alone. It's of that magnitude. I think Don Bateman was saying that they also use lapse rate. I don't think it's quite the same mechanization but I think he had numbers very much along that line.

Q: FRED PROCTOR (MESO) - Low level stable layers can sometimes be present prior and during microburst events. Could your system function properly in such cases?

A: TERRY ZWEIFIL (Honeywell Sperry) - It depends. If you look at, as an example, the 11 July sounding, and you can see that in fact there was a stable layer. It did drop back below the unstable measurement of -0.003 . In this case the system, by having read the previous lapse rate values up in here, has already armed. Then it just sits there and waits to see if the temperature ever swings out the other way, implying that you've flown into the cold down flow. So, even though this phenomenon occurs, it does not disarm the system. It says I saw it once, therefore I'm going to maintain this. Actually, that's not quite true. If we see it long enough, over about 1000 feet that it has dropped below -0.0025 , then it will reset and say there really wasn't a serious problem here. Surely I could conceive of some situation when in fact we wouldn't do exactly what we wanted to do. But in the cases that we have looked at, even with these stable layers, it still performs its intended function.

Q: WAYNE SAND (NCAR) - Can you tell us more about your chip to measure dew point? How accurate is it? How much does it cost? How does it interface with existing air data computers?

A: TERRY ZWEIFIL (Honeywell Sperry) - How accurate is it -- based on our people up in SRC, I understand that it is something of the order of $\pm 5\%$ in measuring relative humidity. Basically the reason we, Honeywell, designed this was that we built a lot of systems to monitor computer rooms and keep them at certain relative humidities and certain temperatures. That's what the chip is built for. It's not in production so I really can't tell you how much it costs. Hopefully, not much. Does it interface with existing air data computers -- not yet, though we have looked into it and I am a little concerned about some of the engineering that goes into that. We certainly have the room to put it inside our computer. Our wind shear computer, by the way, has a complete air data computer of its very own, we don't use anybody else's. How we do that -- haven't got that far. It doesn't seem to me to be an insurmountable problem. It would be a beautiful thing to have. That's one part we're missing.

Q: TON NIEUWPOORT (Fokker Aircraft) - Using a Kalman filter means that the noise characteristics have to be known. How are these noise characteristics determined?

A: TERRY ZWEIFIL (Honeywell Sperry) - He's exactly right and that puzzled me for some time, still does for that matter. Basically the way I did it, a brief explanation. To compute the time constant for a Kalman filter, basically you have to know the variation of the thing that you are measuring and also your measuring equipment. In this case we're really not so much concerned about what is the variance of the temperature probe, we assume that is accurate enough. What we're really trying to do is separate out the lapse rate, that's the signal, from the noise, which is the garbage you get from little eddy's going around in the atmosphere. Basically what I did was back into it almost like a circular reasoning type of thing. I figured out what the number had to be to give the quickest results, to get the filter as fast acting as possible, yet still giving us enough filtering so we don't just get total noise. I could give you the number but it wouldn't I don't think mean a heck of a lot.

Q: PETER SINCLAIR (Colorado State University) - How does your temperature lapse rate sensing device determine what part of the measured temperature change is due to the horizontal and vertical temperature components?

A: TERRY ZWEIFIL (Honeywell Sperry) - The answer to that one is real simple. It doesn't. It assumes that the temperature signature that it measures is simply an indication of a microburst. It does not care whether it's from a vertical or a horizontal sense.

ROLAND BOWLES (NASA Langley) - Isn't that a fairly significant shortfall? When we do soundings we release balloons to get temperature altitude profiles. The idea is that if it goes miles down range it's beginning to get cluttered up. Here an airplane on approach can travel several miles with relatively small altitude change. So are we really getting a lapse rate measurement off that airplane?

TERRY ZWEIFIL (Honeywell Sperry) - Yes, you are. You're not getting a perfectly vertical measurement of lapse rate but then when you really look at the data we have from all these accidents, none of those were done right there at the site.

ROLAND BOWLES (NASA Langley) - Understood, but maybe a significant discriminator is the along-track rate of change of temperature, a thermal plume that's sitting out there and we encroach upon it and there's rapid variation along-track. Maybe that's the give away.

TERRY ZWEIFIL (Honeywell Sperry) - That's Conceivable. Typically on approach you've got about a 3 degree gamma so most of your component is along-track. We do make that tacit assumption that this is not a real small scale type of event. We assume that the atmosphere in fact looks like this uniformly within the region of interest, whatever that might be and, you're right, that is a tacit assumption that we do make.



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16. Abstract <p>The Third Combined Manufacturers' and Technologists' Conference was hosted jointly by NASA Langley Research Center (LaRC) and the Federal Aviation Administration (FAA) in Hampton, Virginia, on October 16-18, 1990. The meeting was co-chaired by Dr. Roland L. Bowles of LaRC and Herbert Schlickemaier of the FAA. The purpose of the meeting was to transfer significant ongoing results of the NASA/FAA joint Airborne Wind Shear Program to the technical industry and to pose problems of current concern to the combined group. It also provided a forum for manufacturers to review forward-look technology concepts and for technologists to gain an understanding of the problems encountered by the manufacturers during the development of airborne equipment and the FAA certification requirements. The present document has been compiled to record the essence of the technology updates and discussions which followed each.</p>					
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